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Determination of soil temperatures from meteorological data

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DETERMINATION OF SOIL TEMPERATURES

FROM METEOROLOGICAL DATA

by

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I. INTRODUCTION

A. The Prediction Problem

The objective of this investigation is to provide a rational method for predicting soil temperatures. Since soil temperatures vary with time and depth, the temperatures had to be measured at specified times and depths. The specified times were daily between 5:00 p.m. and 5:30 p.m., while the depths were at three, six, twelve and twenty-four inches below the soil surface.

The predictors to be utilized in estimating the soil temperatures were selected on the basis of apriori considerations. These predictors include as meteorological factors: air temperature, solar energy, cloudiness, and wind velocity, and as soil factors: soil moisture and two types of soil cover. An attempt was made to discover which of these factors were best related to the temperature of the soil, and to prepare a multiple regression analysis.

B. Deficiency of Soil Temperature Data

Continuous and systematic measurements of soil temperatures are rare. Fitton and Brooks (1931) examined the United States literature and found no continuous records. Later, Zikeev (1951) in a comprehensive review, discovered a few long records of soil temperature in Europe. Currently, the U. S. Weather Bureau (1955a, 1955b) is publishing soil temperature data on a continuous basis from three locations in Iowa and two locations in Missouri.

The deficiency of soil temperature data is due to the difficulty of obtaining measurements. Mercury-in-glass thermometers have been employed, but to prevent breakage these thermometers must be incased in protective material which have thermal properties different from that of soil. Electrical resistance and thermocouple measurements are useful, but expensive interpretative equipment is required. Inexpensive but accurate thermometric measurements of soil temperatures are not at present possible.

The development of a suitable method for predicting the temperature of the soil would make the deficiency of soil temperature data less noticeable. It would reduce the number of soil temperature observing stations, and it would provide a means for constructing systematic and continuous predictions of soil temperature.

C. Importance of Soil Temperatures to Agricultural Production

Plant tissue may be permanently injured by low temperatures. Levitt (1941) has provided a review of the physiological nature of such injury. In some cases the low temperature injury may occur in the root zone because of low soil temperatures. Iverson (1939) has noted such winter injury in the case of strawberries.

The delay in germination and seedling development by low soil temperatures is important. This problem was discussed by Naegler (1913). He noted a relationship between soil temperatures and the coming of spring, where a one degree Centigrade deficiency at one meter delayed spring ten days. Halsted and Waksman (1917) found that the rapidity of corn germination depended upon the temperature of the soil, and Camp and Walker (1927) noted that the cotton seedling development was delayed by cool soil temperatures. Henry (1932) observed a similar growth inhibition to wheat seedlings by low soil temperatures. Plant development beyond the seedling stage is normally not limited by low soil temperatures, but Schroeder (1939) noted that addition of cold water to greenhouse cucumbers reduced their ability to absorb water due to the lower root temperature.

The growth and development of the soil's microbiological species is related to the temperature of the soil. Waksman (1952) reports that the number and kind of organisms present is determined by the temperature of the soil. The activity of microorganisms increases with soil temperature until the optimum temperature is reached. Further temperature increase is accompanied by a decline in the microorganism's activity.

The physical and chemical processes within the soil are also dependent upon its temperature. Jenny (1941) demonstrated the importance of temperature to the development of the soil's morphological characteristics. Eid, Black, and Kempthorne (1951) noted that the rate of release of organic phosphorus was dependent upon the temperature of the soil. Bouyoucos (1915) related such physical processes as water movement and air diffusion to the temperature of the soil.

II. REVIEW OF LITERATURE

A. Modifying Effect of the Soil's Thermal Properties

When the temperature of a body is not uniform, heat will flow from the hotter to the colder portions of the body. Heat transfer in soil is either downward from a relatively warm surface during the day time or upward toward a comparatively cool surface at night. Ingersoll, Zobel, and Ingersoll (1948) discuss this and other related heat transfer problems. They show that the rate of heat flow in a material is given by

$$q = -kA\frac{\partial \theta}{\partial x} \qquad (1)$$

where q is the rate of heat flow

A is the area

θ is the temperature

x is the distance

k is the apparent thermal conductivity of the material. The resulting temperature change also depends on the specific heat, c, and density, ρ, of the material. The thermal diffusivity, α, which is an index of the ease with which a material will undergo temperature change, is related to k, c, and ρ by equation (2),

$$\alpha = \frac{k}{c\rho} \quad . \qquad (2)$$

The constants of equation (2) define the thermal properties which determine the temperature distribution in the soil.

Prior to the twentieth century some attempt was made to measure the soil's thermal properties. Thomson (1861) calculated the thermal conductivity of the earth crust to a depth of twenty-four feet. Callendar and McLoed (1897) determined the thermal diffusivity of soil. These latter investigators found the thermal diffusivity of soil to be high during the spring and fall and low during the winter and summer. The low summer values seemed to be associated with the dry surface soil layer, while the low diffusivities of winter were the result of constant snow cover. These results indicate that more rapid changes in soil temperature occurred during spring and fall than during winter and summer.

Since 1900 other investigators have studied the thermal properties of soils. Patton (1909) examined the variation of the soil's thermal properties with moisture content. He noted that while thermal conductivity increased with increasing moisture content throughout the moisture range, thermal diffusivity increased with increasing moisture only at lower moisture contents. At high moisture content the diffusivity decreased as the percentage of soil moisture was increased. This irregular behavior of thermal diffusivity was attributed to the effect of the high specific heat of the soil-water system at the high moisture contents. These results indicate a complex relationship between soil moisture and soil temperature. At low moisture contents the addition of water would increase capacity of a soil to change temperature, while at high moisture content the reverse would be true.

Using dry soils, Smith and Byers (1938) measured the differences in the thermal conductivity of dry soils. They noted an inverse relationship between porosity and thermal conductivity. Coarser textured soils received heat more rapidly than the finer textured soils.

A comprehensive study of the thermal properties of nineteen different soils and soil materials was conducted by Kersten (1949). He observed that the thermal properties of frozen soil were greatly different from unfrozen soil. In general, the conductivity and diffusivity of frozen soil were greater than for unfrozen soil. At low and moderate moisture contents the diffusivity increases with increasing moisture content, but this is not necessarily true at high moisture contents. Changes in soil density had only a small effect on the thermal diffusivity. Kersten's work indicated that the most rapid temperature changes occurred in frozen soils and in soils with moderate moisture content.

The temperature of the soil is determined by rate of heat exchange in the soil. Ingersoll, Zobel, and Ingersoll (1948) have shown that the temperature at any time is a function of the thermal diffusivity of the soil and the temperature gradient. They give the solution as a differential equation in one dimension,

$$\frac{\partial \theta}{\partial t} = \alpha \frac{\partial^2 \theta}{\partial x^2} . \tag{3}$$

This solution has the boundary condition for a sinusoidal wave applied at the soil surface $(x = 0)$,

$$\theta = \theta_0 \sin \omega t \text{ at } x = 0 \tag{4}$$

and the initial condition

$$\theta = f(x) . \tag{5}$$

In the above equations: θ is temperature

t is time

x is depth

α is thermal diffusivity

θ_0 is the temperature at $t = 0$.

The solution of the differential equation (3) is well known in physics. Keen (1932) gives it as

$$\theta = \theta_0 \, e^{-2\pi x/\lambda} \sin 2\pi\left(\frac{t}{T} - \frac{x}{\lambda}\right) \tag{6}$$

where T is the time period of the wave

λ is the wave length

$\omega = \frac{2\pi}{T}$.

The same solution based on a hydrologic model has been given by Dobrowsky (1944).

Keen suggests that equation (6) is not practicable. It presumes that the material is homogeneous as to its thermal properties. He noted that soil is not homogeneous since it varies in moisture and density with depth. Portman (1955) also noted that thermal diffusivity varied with depth and observed that it was not constant with time. Since equation (6) does not provide a realistic solution other means for obtaining a prediction of the temperature of the soil will be sought.

B. Importance of the Physical Factors of the Soil

It was expected for a long time that the physical condition of the soil would exhibit an effect on the temperature of the soil. Investigating this point Bouyoucos (1913) found little variation in the temperature of soil of different textures during most of the year. It was noted that in spring the coarser textured soils thawed first. One peaty soil did not thaw until ten days after the frost had left the sandy soil. Cultivation had a distinct effect on the temperature of the soil. The uncultivated soil was markedly warmer in summer than cultivated soil, while in winter the temperatures were virtually the same. Later, Bouyoucos (1916) reviewed additional data and confirmed his conclusion that all soils tend to have the same temperature under the same meteorological conditions. Taking the case of peat and sand as an example, the author observed that peat has a black color, low heat conductivity and a high water holding capacity;

while sand exhibits a light color, higher heat conductivity and a low water holding capacity. These properties compensated for each other in such a way that in each soil about the same temperature was observed. Bouyoucos noted that during the spring this uniformity of temperature did not hold. He concluded that unequal temperatures were due to the difference in heat required to melt the ice of the soilwater systems. It was also recognized that topography and soil cover affected the observed soil temperatures.

C. Meteorological Factors

It has long been conceded that meteorological factors are functionally related to the temperature of the soil. An examination of the literature reveals that few attempts have been made to isolate these relationships. These efforts have been associated with the effects of solar energy and air temperature on soil temperature. Apparently, no effort has been made to isolate the effects of cloud cover, wind, or precipitation on soil temperatures.

1. Solar energy

The chief difficulty in relating solar energy to soil temperatures has been the absence of basic observational data.

To overcome this difficulty, Knott (1902) related earth temperatures to calculated solar heat values. He showed that approximately one per cent of the calculated solar heat reaching the surface in England was stored in the soil profile during the summer season. This heat was lost from the soil during the winter.

Siegenthaler (1933) used sunshine duration and cloudiness as indices of solar energy. In winter, soil temperatures were negatively correlated with sunshine duration and positively correlated with cloudiness. Since solar energy varies directly with the sunshine duration and inversely with cloudiness, these correlations seem to indicate a negative relationship between solar energy and soil temperature. This unexpected result is probably due to the interaction between air temperatures and cloudiness. In winter, cloudless days are usually associated with cool air masses, while cloudy days occur more often in warm air masses. No mathematical attempt was made to isolate the effect of air temperature from that of cloudiness. Siegenthaler's results for the summer season were different. Sunshine duration was positively correlated with the temperature of the soil, while the cloudiness was negatively correlated with soil temperatures.

2. Air temperature

Many attempts have been made to relate air temperatures with soil temperatures. Franklin (1919) presented an empirical relationship for determining the temperature of the soil from air temperatures. This equation was intended to provide information on the danger of frost during late spring and early fall. Siegenthaler (1933) found correlation coefficients between air and soil temperatures of the order of .9. He noted that the temperature ten centimeters below the surface was nearly the same as the air temperature in winter, but averaged two degrees Centigrade warmer in summer. Penman (1943) presented on a scatter diagram an excellent agreement between air and soil temperatures. The scattering of points indicate a linear relationship. It was concluded that air temperatures were related to previous soil temperatures. Langbein (1949) presented the solution to a differential equation which related soil and air temperatures. There was good agreement between predicted and observed weekly mean soil temperatures.

Considerable effort has been made to predict the depth of frost penetration by air temperatures. Fuller (1936) outlined a method which used the summation of temperatures below thirty-two degrees Fahrenheit as an index of the depth of frost penetration. Berggren (1943) developed a differential equation which related frost penetration to temperature. Shannon (1945) compared the temperature summation method with that of Berggren. He found that the equation of Berggren consistently overestimated frost penetration, which indicated that some adjustment was necessary. Shannon notes that satisfactory results were obtained by the summation method.

III. PROCEDURES

A. Observational Procedures

1. Soil temperature observations

a. Observational equipment. Soil temperatures were measured with copper-constantan thermocouples. The thermocouples provided accurate point estimates of temperature without the installation of large protective tubes. Copper-constantan was employed because of its stability and effective temperature range. A similar method of observation had been previously successfully used by Mail (1935) and White (1946).

Since copper readily corrodes in the presence of water, it was necessary to protect the thermocouple and thermocouple lead wires from the action of soil water. Each thermocouple was imbedded in a three-eighths inch copper tube. This was accomplished by pinching the tube over the thermocouple and soldering the pinched end. Each thermocouple lead wire was inserted in a Tygon tube to prevent deterioration of the lead wire insulation.

The thermocouple readings were made with a semi-precision portable potentiometer. Leeds and Northrup (1949), manufacturers of the instrument, claim an accuracy of 0.3 per cent of the instrument's range. Since the potentiometer range was 170 degrees Fahrenheit, the expected accuracy was one-half a degree.

b. Observational methods. The soil temperature observations were obtained from six foot square plots located near the Weather Bureau observing station at the Municipal Airport in Columbia, Missouri. There were six plots from which observations were taken. Three of these plots were maintained fallow, while the remaining three remained in grass. The six plots were arranged in three blocks of two plots. The type of cover for each plot was randomly selected with the limitation that each block have one fallow and one grass plot.

The topography of the area is gently rolling, and the plots were located in an area with a very slight slope toward the south. The soil type is Mexico silt loam. This soil, the properties of which have been described by Whiteside and Marshall (1944), is found in association with the Putman silt loam of northeast Missouri. The soil is best known for its tenacious subsoil, which has apparently resulted from the clay accumulation in the upper B horizon.

Soil temperature observations were taken at three, six, twelve, and twenty-four inches below the surface. Two observations were taken at all depths in each plot. The installation of thermocouples was accomplished by drilling a hole to the depth of twenty-four inches, and installing one thermocouple at each of the four depths. The observation points were located in the corners of the center one square foot of each plot. The corner to be used for the first observation point was selected at random, and the second location was placed in the corner diagonally across from the first. In the remaining two corners of the center one square foot, soil moisture blocks were installed. In Figure 1 are shown the locations of thermocouple and moisture block observing points on a plot layout diagram.

The Tygon tubes, which protected the lead wires from the four depths, were inserted into holes of an ordinary fruit jar lid. After the observations had been recorded, the lead wires were placed inside a one-quart fruit jar, and the jar was screwed on to the lid. The end of the thermocouple lead wires were protected by the jar between observation times.

Each day six observations were taken at every depth under each type of cover, making a total of forty-eight daily thermocouple observations. It required approximately thirty minutes to record the temperatures from all thermocouples. A system of randomization of the order of reading the thermocouples was derived, so that the temperatures from each location were observed in each order the same number of times. The daily average temperature at each depth under grass and fallow covers are given in Appendix A. Each of these values is the average of six observations.

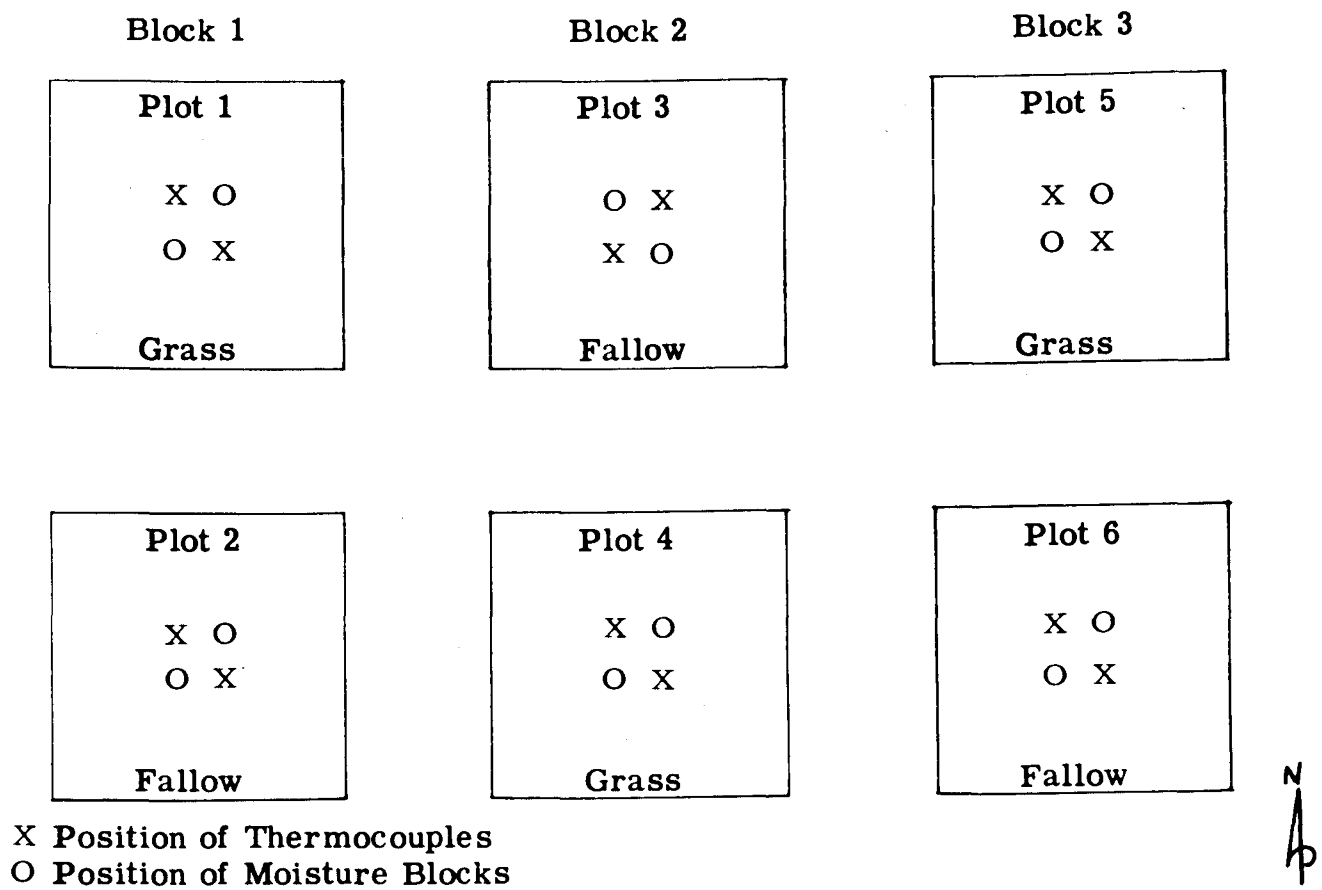

Figure 1. Diagram of soil temperature observation plots showing the location of the thermocouples.

2. Soil moisture observations

a. Method of measurement. It has been observed that the thermal properties of soils vary with the moisture content. Thermal conductivity increases with increasing moisture contents over the entire soil moisture range; while thermal diffusivity increases with moisture content at the low soil moisture values. In order to develop an adequate means of estimating the temperature of the soil it is necessary to obtain a measurement related to the soil's moisture content. Bouyoucos and Mick (1940) reported field trials on the use of gypsum blocks to measure soil moisture. This method, which is widely used in soil moisture studies, is based on the measurement of the electrical resistance between two electrodes imbedded in a gypsum block. When the gypsum blocks are placed in the soil, a moisture equilibrium is established between the block and soil system; so the moisture content of gypsum block is related to the moisture content of the soil. Since the electrical resistance of the gypsum block decreases with increasing moisture content, there is an indirect relationship between the block's electrical resistance and the moisture content of the soil.

b. Observational method. Two gypsum blocks were installed at three, six, twelve and twenty-four inches below the surface of each plot. The positions at which these blocks were placed are shown in the plot layout diagram in Figure 1.

The moisture content of the soil did not change every day. This was particularly true during the winter when there was low precipitation and little opportunity of evaporation. Resistance readings were not collected on most winter days since no moisture change was anticipated. During other seasons of the year the moisture content of the fallow plots varied little from day to day, so measurements within all the fallow plots were not made daily. Resistance readings for those days when observations were not taken were estimated by a simple graphic method. Since electrical resistance also varies with temperature, the electrical resistances used as a measure of soil moisture were corrected to a standard temperature. White (1946) reported Peele and Beale as evaluating the relationship of temperature to the electrical resistance of the gypsum block as,

$$\log R_e = \left[1 + .002\,(\theta_o - \theta_c)\right] \log R_o \qquad (7)$$

where R_e is the electrical resistance corrected to θ_c, the standard temperature,

R_o is the electrical resistance measured at θ_o, the soil temperature at observation time.

Each observed and estimated electrical resistance was corrected to a standard temperature of 80 degrees Fahrenheit according to Equation (7). In Appendix B the mean daily electrical resistances are shown.

3. Meteorological measurements

a. Description of weather stations. Meteorological measurements were taken at government weather stations. The U. S. Weather Bureau (1951) has published instructions for the observing procedures and a description of the weather instruments used to obtain the measurements. The air temperatures were measured in standard instrument shelters. The shelter at the Weather Bureau's installation in Columbia, Missouri is located over a grass surface near an airport apron. The anemometer used for measuring the wind velocity at Columbia is located on a roof forty-eight feet above the ground. Solar energy was measured by a pyrheliometer which was also exposed on the roof.

b. Air temperature observations. A functional relationship exists between the temperature of the soil and the temperature of the air mass above the soil surface. One method of describing this relationship is to consider the temperature of the soil as a function of the temperature of the invading air and as a function of the previous air temperatures over the area. It is reasonable that cold air moving over a warm surface would produce warmer soil temperatures than would cold air moving over a cold surface. The temperature of the invading air was taken to be the temperature of the air found

23 hours earlier upstream from Columbia, Missouri, or at 6:30 p.m. on the previous day. The previous air temperature over the area was selected as the 6:30 p.m. Columbia, Missouri temperature on the day previous to the soil temperature observations.

To obtain the temperature of the invading air at 6:30 p.m. on the previous day, it was necessary to trace trajectory of the air movement. A method for finding the trajectories from the measured geostraphic wind was described by Petterssen (1940). Trajectories were prepared by six hourly intervals, 6:30 p.m., 12:30 a.m., 6:30 a.m. and 12:30 p.m., from the CST synoptic weather maps. These maps were the fascimile reproductions of the maps prepared by the Weather Bureau, Air Force and Navy Analysis Center in Washington, D.C. By this means, the movement of the air over Columbia at the time of the soil temperature observation was traced upstream to its position 23 hours earlier. The air temperature reported at government weather station nearest to this upstream location at 6:30 p.m. CST on the day previous to the soil temperature observation was taken as the temperature of the invading air. The weather stations, whose data were utilized, are shown in Figure 2. The 6:30 p.m. Columbia air temperature on the day previous to the observation was used as the previous air temperatures over the area.

A second method for describing the functional relation-

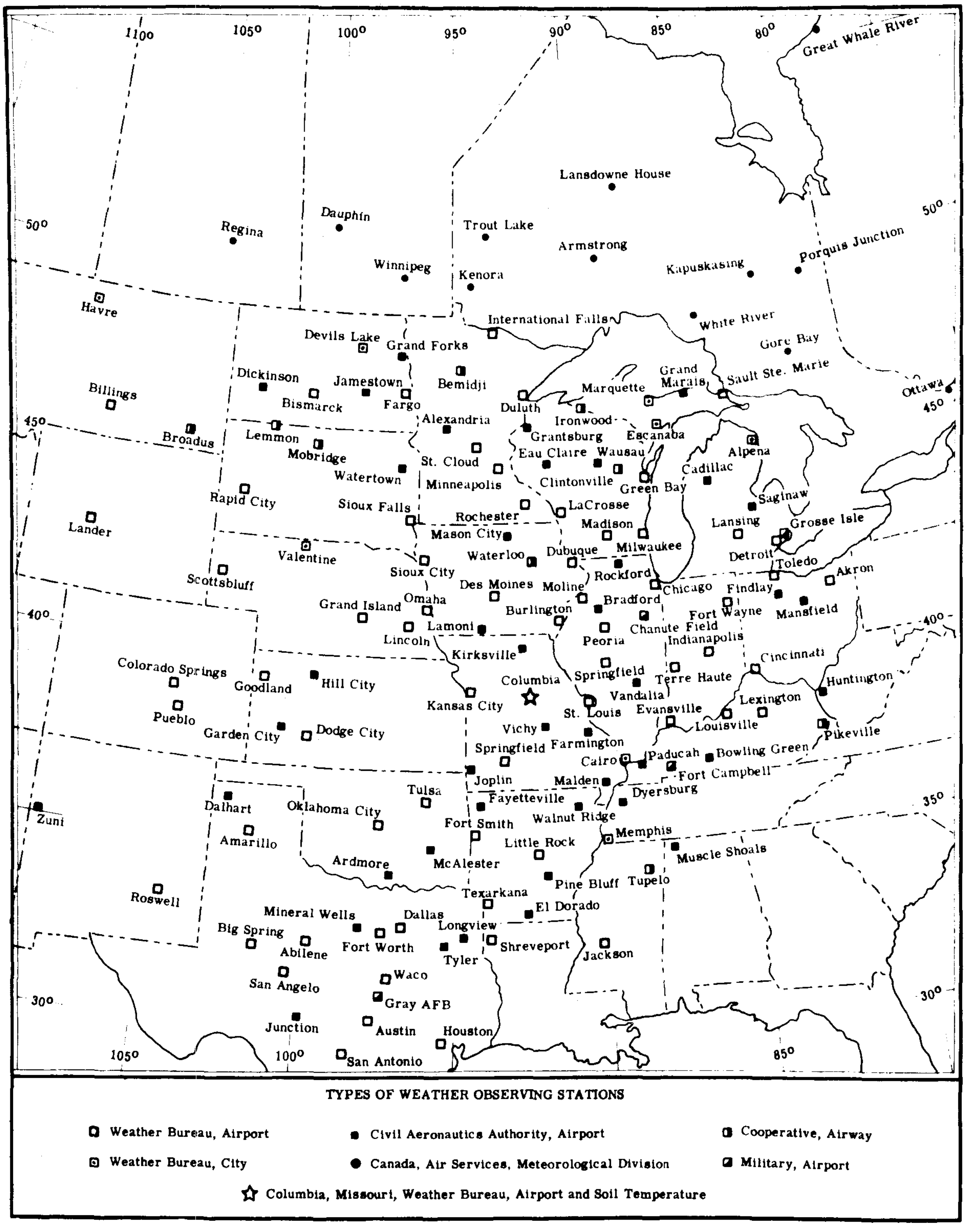

Figure 2. Weather stations from which upstream air temperatures were obtained.

ship between air mass and soil temperatures is to relate the soil temperature to the air temperature occurring at the same time. This method is simpler since it requires only one observation, and this method has been used previously by other investigators. The chief difficulty with this simpler method is that it is impossible to separate the effect of the temperature of the invading air. The 5:30 p.m. Columbia air temperatures for each day with soil temperature observations were used as the air temperatures current with the soil temperature observations.

The temperature of the deeper soil layers lags behind the temperatures nearer the surface. This lag has been estimated by Bliss (1942), Callender and McLoed (1897), Decker (1953), Keen (1931), McKenzie-Taylor and Williams (1924), Russell (1950) and Wollny (1878). These estimates have been plotted on Figure 3 and a smooth curve was fitted to the data. It is indicated from this figure that:

(1) The six inch soil temperatures are determined by the air temperatures three hours earlier.

(2) The twelve inch temperatures are determined by the air temperatures ten hours earlier.

(3) The twenty-four inch temperatures are determined by the air temperatures thirty-two hours earlier.

Since in this investigation the soil temperatures were taken at 5:00 to 5:30 p.m., it seems reasonable that the six inch

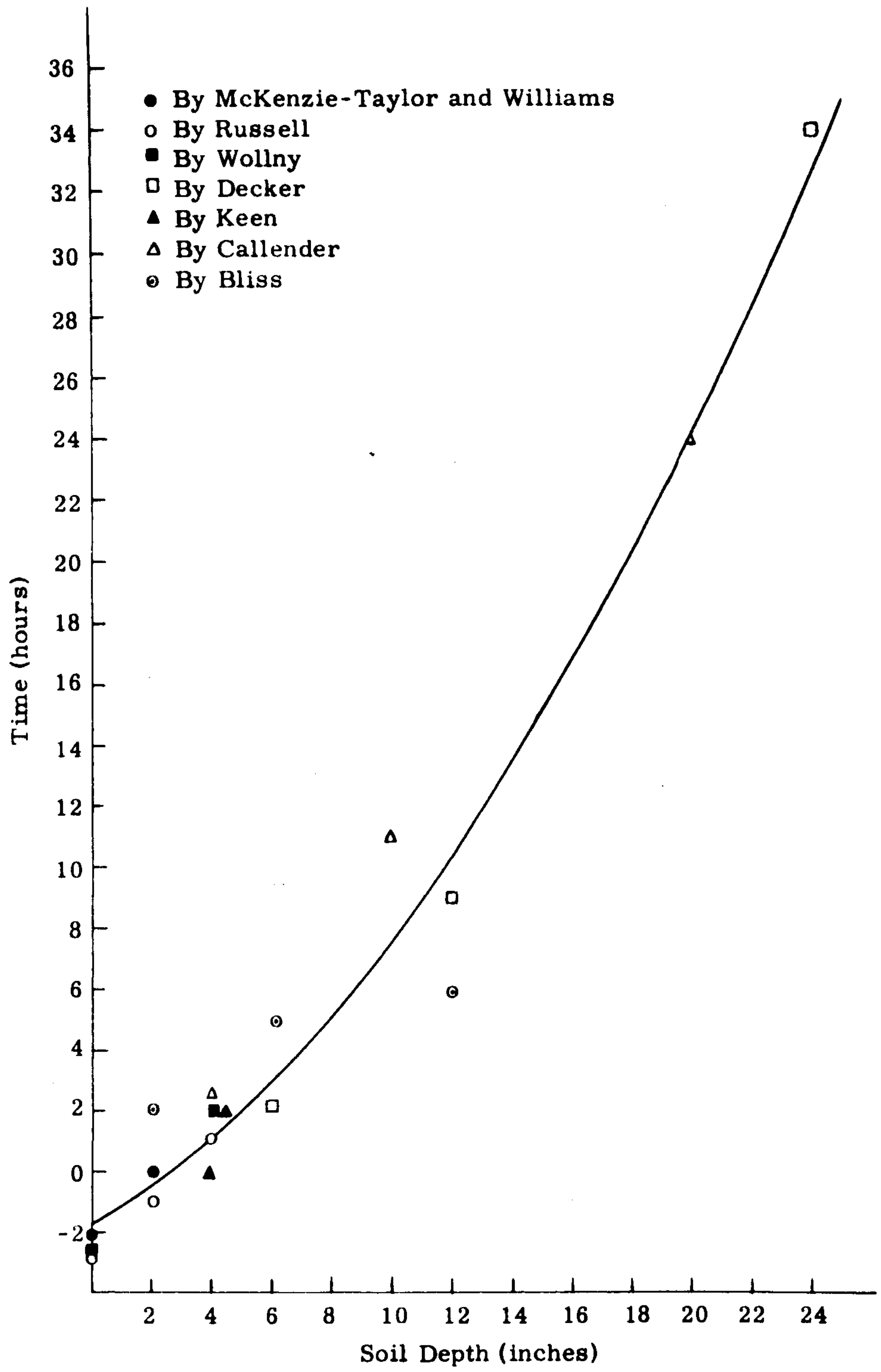

Figure 3. Time lag between the air temperature at five feet above the surface and the temperature at selected depths below the surface.

temperature should be best related to the 2:30 p.m. air temperature, the twelve inch temperature should be determined by the 7:30 a.m. temperature, while the twenty-four inch temperature should be related to the 9:30 a.m. temperature the previous day. The air temperatures for Columbia for these three hours were used for these temperature variables.

c. Solar energy observations. The amount of solar energy received determines the amount of heat available for warming the soil. On days when the solar energy is high, more energy is available for absorption and higher soil temperatures are expected than on days with low insolation. The data used were the daily energy values in gram calories per square centimeter per day obtained at Columbia for each day with soil temperature observations.

d. Night cloudiness observations. Late in the day the outgoing terrestrial radiation becomes dominant over the incoming solar energy. At darkness the solar energy no longer reaches the earth's surface while terrestrial radiation from the surface continues throughout the night. Cloudiness is important in controlling the amount of heat lost from the surface by terrestrial radiation. Increasing the amount of sky cover reduces the amount of energy lost from the surface by this radiational process and will result in higher soil temperatures. The average night cloudiness was computed from the thirteen regular hourly observations from 6:30 p.m. to

6:30 a.m. at Columbia.

e. Wind observations. Air movement provides another mechanism for the transfer of heat at the surface. A strong wind is associated with a rapid heat transfer, and usually results in lower soil temperatures. The average wind speeds for the twenty-four regular hourly observations between 5:30 p.m. of the day previous to the observation and 4:30 p.m. of the day with a soil temperature observation were computed for Columbia.

B. Statistical Procedures

1. Nomenclature for the statistical analysis

The problem under consideration is the development of equations for predicting the average temperature of the soil at selected depths. The dependent variables are the average soil temperatures listed in Appendix A. The Greek letter theta, θ, is used to designate soil temperature observation. Primes are used for variables measured under fallow cover, while the absence of primes refers to measurements under a grass cover.

(a) θ_3 the average daily three inch soil temperature under grass.

(b) θ_6 the average daily six inch soil temperature under grass.

(c) θ_{12} the average daily twelve inch temperature under grass.

(d) θ_{24} the average daily twenty-four inch temperature under grass.

In the cases where the dependent variables are identified as θ'_3, θ'_6, θ'_{12} and θ'_{24}, the temperatures are the three, six, twelve and twenty-four inch temperatures under fallow soil.

Meteorological factors and the soil moisture electrical resistance were used as independent variables. For brevity the following symbols have been applied to these factors;

(a) T_1 the air temperature at Columbia, Missouri at 6:30 p.m. on the day previous to the soil temperature observation.

(b) T_u the temperature which the air over Columbia, Missouri at the observation time had at 6:30 p.m. upstream on the previous day.

(c) T_2 the air temperature at Columbia, Missouri at 5:30 p.m. on the same day as the soil temperature observation.

(d) T_3 the air temperature at Columbia, Missouri at 2:30 p.m. on the same day as the soil temperature observation.

(e) T_4 the air temperature at Columbia, Missouri at 7:30 a.m.

(f) T_5 air temperature at Columbia, Missouri at 9:30 a.m. on the day previous to the soil temperature observation.

(g) S the total solar energy reaching the surface each day at Columbia, Missouri.

(h) C the average cloudiness during the night previous to the soil temperature observation at Columbia, Missouri.

(i) W the average wind speed for the twenty-four hour period ending at the time of the soil temperature observation.

(j) M_i the soil moisture electrical resistance under grass cover where i refers to depth of measure.

(k) M_i' the soil moisture electrical resistance under fallow soil where i refers to the depth of measurement.

2. Models for the statistical analysis

The statistical analysis was conducted to provide a method for determining the functional relationship between the average soil temperatures at selected depths and the independent variables. The models for the analysis were redefined for each depth on the basis of reasonable considerations.

Two models were presented for the prediction analysis of the three inch soil temperatures. In the first, the three inch soil temperatures θ_3 and θ_3' are related to the temperature T_u of the invading air, the previous air temperature T_1, and the other independent variables as:

$$\hat{\theta}_3 = f(T_1,\ T_u,\ S,\ C,\ W,\ M_3)$$
$$\hat{\theta}_3' = f(T_1,\ T_u,\ S,\ C,\ W,\ M_3')\ .$$

The second model is like the first except that the air temperature at the time of observation T_2 replaces T_1 and T_u.

$$\hat{\theta}_3 = f(T_2,\ S,\ C,\ W,\ M_3)$$
$$\hat{\theta}_3' = f(T_2,\ S,\ C,\ W,\ M_3')$$

When the functional relationship for each model is derived, comparisons will be possible for determining which model gives the more suitable results under fallow and grass conditions.

For the prediction of the soil temperature at the deeper levels a simpler model is proposed. At these levels the soil temperature is presumed to be related to the air temperature occurring at an earlier time due to the time lag T_j between temperature and depth, the soil moisture M_j at the depth, and the soil temperature θ_j at next higher level. The statistical models for these analyses become:

$$\hat{\theta}_6 = f(T_3,\ M_6,\ \theta_3)$$
$$\hat{\theta}_6' = f(T_3,\ M_6,\ \theta_3')$$
$$\hat{\theta}_{12} = f(T_4,\ M_{12},\ \theta_6)$$
$$\hat{\theta}_{12}' = f(T_4,\ M_{12}',\ \theta_6')$$

$$\hat{\theta}_{24} = f(T_5, M_{24}, \theta_{12})$$
$$\hat{\theta}'_{24} = f(T_5, M_{24}, \theta'_{12}) \, .$$

3. Procedures for the statistical analysis

On the basis of the previously listed models ten separate analyses were necessary. Because of the amount of data, these analyses could not be conducted by ordinary procedures. Data from the Appendix were placed on I.B.M. punch cards, and many of the tabulations were made by machine procedures. This method of tabulation provided a quick and error-free analysis.

The procedure employed was a multiple regression analysis. To obtain the regression analysis the system of Gaussian Multipliers was used, since it provided excellent checks and computational safeguards. A complete and simple description of this method for computation of the multiple regression analysis was outlined by Ostle (1954).

In a preliminary analysis the independent variables were related to the three inch soil temperature increase from one day to the next. Since only fair results were obtained, it was decided to investigate the possibility of gaining an improvement by conducting the analysis according to season. The year was divided into four seasons, and a separate analysis was prepared for each season. The winter season comprised observations for December, January and February. The spring analyses were taken from observations recorded in March, April and May. Summer was defined as June, July and August, while fall was made up of September, October and November. The number of regression analyses was increased to forty, since ten were necessary for each season.

IV. RESULTS

A. Prediction of the Three Inch Soil Temperature

1. Prediction analysis under grass cover

a. Analysis which employed the temperature of the invading air and previous air temperature. According to the previously presented model the three inch soil temperature under grass is functionally related to six variables. These variables are: T_u, the temperature of the invading air; T_1, the previous air temperature; S, the total daily solar energy; C, the average night cloudiness; W, the average daily wind velocity; and M_3, the average three inch soil moisture resistance under the grass cover.

The simple correlation coefficients, which show the relationship between all variables, are shown in Table 1. These correlation coefficients indicate a consistent relationship between the dependent and the independent variables. The three inch soil temperature is significantly correlated with T_u and T_1, during all seasons, and with S, W and M_3 on three out of four seasons. Only C failed to be significantly correlated with the three inch soil temperature under grass during all seasons. These correlation coefficients also exhibit a marked relationship between the independent variables.

Table 1. Simple correlation coefficients used in relating the three inch soil temperature under grass θ_3 to T_u, T_l, S, C, and M_3

Variable	T_u	T_l	S	C	W	M_3
Winter						
θ_3	.403**	.778**	.229	-.145	.336**	-.330*
T_u		.270*	-.069	-.065	-.050	-.273*
T_l			.021	-.020	.412**	-.300*
S				-.483	-.045	-.408**
C					.165	.021
W						-.046
Spring						
θ_3	.726**	.837**	.350**	-.062	-.262	.164
T_u		.614**	.053	-.018	-.289*	.257*
T_l			.033	.005	-.026	.175
S				-.505**	-.333	.033
C					.351**	-.106
W						.044
Summer						
θ_3	.622**	.713**	.564**	-.100	-.261*	.496**
T_u		.493**	-.255*	-.215*	-.214*	.318**
T_l			.143	-.067	.086	.442**
S				-.393**	-.262*	.098
C					.182	-.058
W						.012
Fall						
θ_3	.791**	.912**	.769**	-.208	-.195	.411**
T_u		.679**	.454**	-.294*	-.321*	.417**
T_l			.618**	-.126	-.010	.391**
S				-.347	-.228	.073
C					.388*	-.081
W						-.130

*Correlation coefficients significant at the five per cent level.

**Correlation coefficients significant at the one per cent level.

This interdependence between the independent variables is most marked in the case of T_u, which is significantly correlated with all other variables during the summer and fall seasons.

The regression analysis was conducted through the use of the correlation coefficients of Table 1. A correlation coefficient matrix was formed; and using the method described by Ostle (1954), this matrix was transformed into one containing the Gaussian multipliers. The Gaussian multipliers were used to compute the multiple correlation coefficients, partial regression coefficients, and other useful statistics.

The computed multiple correlation coefficients, R, for the analysis of each season are listed in Table 2. Also presented in this table are the squares of the multiple correla-

Table 2. Multiple correlation coefficients and standard errors of estimate for the regression analysis of three inch grass soil temperature θ_3 using T_u, T_1, S, C, W, and M_3 as independent variables

Season	R	R^2	Standard error of estimate
Winter	.836	.6994	3.64
Spring	.942	.8864	3.53
Summer	.923	.8524	2.27
Fall	.975	.9511	2.68

tion coefficients which indicate the percentage of the total variation explained by the independent variables, and the standard errors of estimate. The latter statistic indicates the precision associated with the prediction equation and it is used as a basis for the computation of the standard errors of the partial regression coefficients.

The partial regression coefficients found in this analysis are listed in Table 3, along with the standard errors of each partial regression coefficient. These standard errors were used in the computation of the t-statistics which were used in testing for the significance of the partial regression coefficients. The partial regression coefficients for T_u, T_l and S tested significantly different from zero for all seasons. The significance of the remaining partial regression coefficients varied from season to season. Variables, which produced insignificant partial regression coefficients, were removed; and a new multiple regression analysis was computed. Table 4 lists the multiple correlation coefficients based on these variables. A comparison of Table 4 with Table 2 reveals that the removal of the insignificant variables did'nt materially reduce the correlation coefficients. The computed multiple correlation coefficient for the fall season shown in Table 4 is 0.001 larger than the corresponding coefficient in Table 2. This is theoretically impossible, and must be due to rounding errors in the computation of Gaussian multipliers.

Table 3. Partial regression coefficients and their standard errors used in the prediction of the three inch soil temperature under grass

Season	Statistic	Variable T_u	T_1	R	C	W	M_3
Winter	Regression coefficient	.090***	.310***	.014**	-.0085	.152	.00026
	Standard error	.041	.030	.0054	.146	.164	.00043
Spring	Regression coefficient	.161***	.466***	.018***	.398***	-.258*	-.000047
	Standard error	.036	.043	.0027	.143	.152	.00015
Summer	Regression coefficient	.115***	.378***	.018***	.374***	-.401**	.0000015***
	Standard error	.029	.041	.0019	.088	.105	.00000039
Fall	Regression coefficient	.190***	.375***	.028***	.288**	-.129	.0000023**
	Standard error	.031	.042	.0033	.120	.139	.00000094

***Significant at the one per cent level.
**Significant at the five per cent level.
*Significant at the ten per cent level.

Table 4. Multiple correlation coefficients of three inch soil temperature under grass with independent variables as indicated

Season	Independent variables	R	R^2
Winter	T_u, T_1, S	.833	.6943
Spring	T_u, T_1, S, C, W	.941	.8862
Summer	T_u, T_1, S, C, W, M_3	.923	.8524
Fall	T_u, T_1, S, C, M_3	.976	.9529

The least squares solution of the regression analysis is

$$\hat{\theta}_3 = b_o + b_1T_u + b_2T_1 + b_3S + b_4C + b_5W + b_6M_3 \qquad (8)$$

where $\hat{\theta}_3$ is the estimated three inch soil temperature under grass, and

$$b_o = \bar{\theta}_3 - b_1\bar{T}_u - b_2\bar{T}_1 - b_3\bar{S} - b_4\bar{C} - b_5\bar{W} - b_6\bar{M}_3 \qquad (9)$$

where the bars denote the sample means. A separate regression analysis is available for each season of the year, and are shown in equations (10) through (13).

Winter: $\hat{\theta}_3 = 23.00 + .080T_u + .322T_1 + .012S \qquad (10)$

Spring: $\hat{\theta}_3 = 16.89 + .159T_u + .466T_1 + .018S + .404C - 266W \qquad (11)$

Summer: $\hat{\theta}_3 = 32.91 + .144T_u + .378T_1 + .018S + .374C - 401W + .0000015\,M_3 \qquad (12)$

Fall: $\hat{\theta}_3 = 17.37 + .201T_u + .360T_1 + .029S + .258C + .0000024\,M_3 \qquad (13)$

b. <u>Analysis which employed the air temperature occurring at the time of the soil temperature observation</u>. According to the hypothesis of the second model the three inch soil temperature is related to five variables. In this analysis the air temperature, T_2, at the time of the soil temperature observations is employed in place of T_u and T_1. All other variables are the same as before and consist of S, C, W, and M_3.

The additional correlation coefficients needed to form the correlation matrix for this analysis are shown in Table 5. These correlation coefficients, which exhibited a marked interrelationship between T_2 and the other variables, were

Table 5. Simple correlation coefficients relating to the air temperature T_2 at the time of the soil temperature observation with the other variables

	Variable				
Season	θ_3	S	C	W	M_3
Winter	.762**	.098	-.175	.104	-.342**
Spring	.856**	.309*	-.170	-.307*	.272*
Summer	.867**	.528**	-.176	-.169	.515**
Fall	.956**	.699**	-.256*	-.180	.386**

**Significant at the one per cent level.
*Significant at the five per cent level.

used to complete the multiple regression analysis. The multiple correlation coefficients obtained are shown in Table 6, and they are smaller than those appearing in Table 2. This indicates that a larger per cent of the variation was

Table 6. Multiple correlation coefficients and standard errors of estimate for the regression analysis of the three inch grass temperature θ_3 using T_2, R, C, W, and M_3 as independent variables

Season	R	R^2	Standard error of estimate
Winter	.821	.6736	3.76
Spring	.874	.7631	5.04
Summer	.897	.8044	2.60
Fall	.972	.9448	2.82

explained through the use of T_u and T_1 than was explained when only T_2 was employed.

The partial regression coefficients and their standard errors are given in Table 7. All of the partial regression coefficients for T_2 and S are significantly different from zero, if the ten per cent level of significance is accepted. In three out of the four seasons partial regression coefficients for C and W were significant, while the partial regression coefficients for M_3 were significant during only two seasons. All variables, which failed to yield significant

Table 7. Partial regression coefficients and their standard errors for predicting the three inch soil temperatures under grass

Season	Statistic	Variable T_2	S	C	W	M_3
Winter	Regression coefficient	.368***	.0099*	.045	.504***	.000010
	Standard error	.044	.0054	.152	.153	.00043
Spring	Regression coefficient	.639***	.0085**	.421**	.0052	-.00017
	Standard error	.056	.0039	.203	.207	.00022
Summer	Regression coefficient	.512***	.0080***	.246**	-.258**	.0000011**
	Standard error	.051	.0025	.101	.116	.00000048
Fall	Regression coefficient	.532***	.020***	.327**	-.081	.0000030***
	Standard error	.035	.0037	.124	.134	.00000098

***Significant at the one per cent level.
**Significant at the five per cent level.
*Significant at the ten per cent level.

partial regression coefficients, were rejected; and a new analysis was computed using the remaining variables. The new multiple correlation coefficients are listed in Table 8, and comparison with Table 6 shows that almost no information was lost through the removal of the variables.

Table 8. Multiple correlation coefficients of the three inch soil temperature under grass with the indicated independent variables

Season	Independent variables	R	R^2
Winter	T_2, S, W	.820	.6730
Spring	T_2, S, C	.872	.7607
Summer	T_2, S, C, W, M_3	.897	.8044
Fall	T_2, S, C, M_3	.972	.9444

From this analysis a set of regression equations were obtained. These equations, which are shown in equations (24) through (27), are similar to equations (20) through (23), except that T_2 is employed as a predictor instead of T_u and T_1.

Winter: $$\hat{\theta}_3 = 17.46 + .366T_2 + .0092S + .512W \qquad (14)$$

Spring: $$\hat{\theta}_3 = 15.03 + .627T_2 + .0088S + .437C \qquad (15)$$

Summer: $$\hat{\theta}_3 = 35.05 + .512T_2 + .0080S + .246C - .258W + .0000011M_3 \qquad (16)$$

Fall: $$\hat{\theta}_3 = 19.95 + .532T_2 + .021S + .301C + .0000030M_3 \qquad (17)$$

2. Prediction analysis under fallow cover

a. Analysis which employed the temperature of the invading air and the previous air temperature. The model for this analysis indicates that three inch temperatures under fallow soil is related to: T_u, the temperature of the invading air mass; T_1, the previous air temperature; S, the total daily solar energy; C, the average night cloudiness; W, the average daily wind velocity; and M_3', the average soil moisture resistance three inches below the fallow surface.

The correlation coefficients which related the three inch fallow temperature and the three inch soil moisture resistance to other variables are shown in Table 9. Other correlation coefficients needed to form the correlation matrix are given in Table 1. The computed multiple correlation coefficients obtained in this analysis are listed in Table 10. The multiple correlation coefficients are approximately equal to those found for grass cover, but the standard errors of estimate for the fallow analysis are consistently larger. This is indicative of a larger variability of the temperature under a fallow soil.

The partial regression coefficients, obtained in this analysis are listed in Table 11. All variables not producing partial regression coefficients significant at the ten per cent level were removed from the analysis, and a new regres-

Table 9. Simple correlation coefficients for relating the three inch soil temperature θ'_3 under fallow and the three inch soil moisture M'_3 with the other variables

Season	Variable	Variable T_u	T_1	S	C	W	M_3
Winter	θ'_3	.434**	.773**	.246	-.180	.289*	-.326*
	M'_3	-.170	-.200	-.043	-.062	-.167	
Spring	θ'_3	.718**	.792**	.378**	-.128	-.259*	.231
	M'_3	.029	.041	.281*	-.295	-.098	
Summer	θ'_3	.588**	.621**	.611**	-.206	-.348**	.705**
	M'_3	.303	.385**	.192	-.091	-.178	
Fall	θ'_3	.802**	.923**	.739**	-.248*	-.193	.420**
	M'_3	.390**	.360**	.102	-.273	-.110	

**Significant at the one per cent level.
*Significant at the five per cent level.

Table 10. Multiple correlation coefficients and the standard errors of estimate for the regression analysis of three inch fallow temperature θ'_3 using T_u, T_1, S, C, W, and M'_3 as independent variables

Season	R	R^2	Standard error of estimate
Winter	.856	.7319	4.15
Spring	.920	.8459	4.44
Summer	.953	.9079	2.34
Fall	.975	.9508	3.18

Table 11. Partial regression coefficients and their standard errors for the regression analysis of the three inch soil temperature under fallow

Season	Statistic	Variable T_u	T_l	S	C	W	M_3^+
Winter	Regression coefficient	.104***	.363***	.014**	-.112	.052	-.0066
	Standard error	.033	.045	.0053	.161	.188	.0034
Spring	Regression coefficient	.200***	.445***	.018***	.298	-.172	.0077
	Standard error	.044	.054	.0034	.181	.188	.011
Summer	Regression coefficient	.120***	.333***	.022***	.224**	-.497***	.011***
	Standard error	.029	.042	.0020	.091	.110	.00094
Fall	Regression coefficient	.216***	.497***	.026***	.169	-.166	.0060***
	Standard error	.037	.049	.0039	.148	.163	.0021

***Significant at the one per cent level.
**Significant at the five per cent level.
*Significant at the ten per cent level.

sion analysis was obtained. The new analyses resulted in the multiple correlation coefficients listed in Table 12. These coefficients are nearly as large as those shown in Table 10 with the greatest reduction occurring for the winter season when two per cent less variability was explained by the independent variables.

Table 12. Multiple correlation coefficients for the three inch soil temperature $\hat{\theta}_3$ under fallow with selected independent variables

Season	Independent variables	R	R^2
Winter	T_u, T_1, S	.844	.7117
Spring	T_u, T_1, S	.907	.8224
Summer	T_u, T_1, S, C, W, M_3'	.953	.9079
Fall	T_u, T_1, S, M_3'	.976	.9525

In equations (18) through (21) are found relationships for estimation of the three inch temperatures under fallow soil.

Winter: $\hat{\theta}_3' = 18.38 + .112T_u + .381T_1 + .016S$ (18)

Spring: $\hat{\theta}_3' = 16.13 + .214T_u + .438T_1 + .018S$ (19)

Summer: $\hat{\theta}_3' = 27.47 + .120T_u + .333T_1 + .022S + .224C - .497W + .011M_3'$ (20)

Fall: $\hat{\theta}_3' = 5.92 + .226T_u + .493T_1 + .025S + .0056M_3'$ (21)

b. <u>Analysis which employed the air temperature occurring at the time of the soil temperature observation</u>. A model has been presented which suggests that the temperature T_2 of the air at the time of the soil temperature observation may be employed instead of T_u and T_1, for the prediction of the three inch temperature under fallow soil. In Table 13 are presented the simple correlation coefficients which relate

Table 13. Simple correlation coefficients for relating T_2 with θ_3' and M_3'

Season	Variable	
	θ_3'	M_3'
Winter	.776**	-.189
Spring	.913**	.144
Summer	.861**	.497**
Fall	.965**	.399**

the three inch soil temperature under fallow to T_2 and M_3', and the other correlation coefficients needed for this analysis are listed in Tables 1 and 9. Using these correlation coefficients a multiple regression analysis was made, and the resulting multiple correlation coefficients are shown in Table 14.

This analysis provided the partial regression coeffi-

Table 14. Multiple correlation coefficients and standard errors of estimate for the regression analysis of the three inch fallow temperature using T_2, S, C, W, and M_3' as independent variables

Season	R	R^2	Standard error of estimate
Winter	.836	.6985	4.36
Spring	.928	.8602	4.20
Summer	.951	.9049	2.36
Fall	.971	.9421	3.41

cients listed in Table 15 for each season. In some respects these partial regression coefficients are different from those obtained earlier. For the first time the coefficients for M_3' during the winter and spring season tested significant at the ten per cent level. This is the only analysis with a non-significant partial regression coefficient for C during the summer season.

As before the variables which produced insignificant partial regression coefficients were removed and a new regression analysis was computed. The multiple correlation coefficients from this new analysis are shown in Table 16. Equations (22) through (25) give the resulting prediction equations.

Winter: $\hat{\theta}_3' = 22.31 + .437T_2 + .011S + .456W - .0070M_3'$ (22)

Table 15. Partial regression coefficients and their standard errors for predicting the three inch soil temperature under fallow

Season	Statistic	Variable				
		T_2	S	C	W	$M_3^{\dagger}$
Winter	Regression coefficient	.435***	.011*	-.028	.461**	-.0071*
	Standard error	.048	.0055	.170	.179	.0036
Spring	Regression coefficient	.724***	.0077**	.321*	.097	.0060*
	Standard error	.045	.0033	.171	.170	.0032
Summer	Regression coefficient	.508***	.012***	.100	-.400***	.0093***
	Standard error	.044	.0022	.091	.106	.0010
Fall	Regression coefficient	.688***	.016***	.220	-.073	.0054**
	Standard error	.043	.0045	.156	.162	.0023

***Significant at the one per cent level.
**Significant at the five per cent level.
*Significant at the ten per cent level.

Table 16. Multiple correlation coefficients of the three inch soil temperature θ_3 under fallow with the indicated independent variables

Season	Independent variables	R	R^2
Winter	T_2, S, W, M_3'	.836	.6990
Spring	T_2, S, W, M_3'	.927	.8597
Summer	T_2, S, W, M_3'	.951	.9037
Fall	T_2, S, M_3'	.970	.9409

Spring: $\hat{\theta}_3' = 6.73 + .718T_2 + .0075S + .342C + .0061M_3'$ (23)

Summer: $\hat{\theta}_3' = 28.89 + .511T_2 + .011S - .391W + .0093M_3'$ (24)

Fall: $\hat{\theta}_3' = 10.14 + .695T_2 + .014S + .0046M_3'$ (25)

B. Prediction of Six Inch Soil Temperature

1. Prediction analysis under grass cover

The model for this prediction analysis indicates that the six inch grass temperature is predictable from T_3, the air temperature three hours prior to the soil temperature observation; M_6, the six inch soil moisture under grass; and θ_3 the three inch soil temperature under the grass cover.

The regression analysis was completed by using the simple correlation coefficients listed in Table 17. During

Table 17. Simple correlation coefficients used in relating the six inch soil temperature under grass with T_3, M_6, and θ_3

Season	Variable	Variable T_3	M_6	θ_3
Winter	θ_6	.668**	.291*	.967**
	T_3		.130	.766**
	M_6			.171
Spring	θ_6	.746**	.011	.979**
	T_3		.247	.832**
	M_6			.042
Summer	θ_6	.827**	.522**	.969**
	T_3		.548**	.871**
	M_6			.595**
Fall	θ_6	.889**	.289*	.992**
	T_3		.280*	.927**
	M_6			.317*

**Significant at the one per cent level.
*Significant at the five per cent level.

winter and fall and summer all three independent variables were significantly correlated with the six inch soil temperature under grass, while in spring the correlation coefficient for M_3 failed to reach the accepted significance level. There was also a marked interrelationship between the independent variables, with all variables during spring and fall being significantly correlated.

The multiple correlation coefficients obtained from this analysis are shown in Table 18. These correlation coefficients are higher than those obtained in the prediction analyses for

Table 18. Multiple correlation coefficients and standard errors of estimate for relating the six inch soil temperature θ_6 under grass to T_3, M_6, and θ_3

Season	R	R^2	Standard error of estimate
Winter	.982	.9640	.97
Spring	.988	.9754	1.49
Summer	.971	.9434	1.16
Fall	.996	.9913	.97

the three inch temperature under grass. The resulting partial regression coefficients are listed in Table 19. The partial regression coefficients for T_3 are negative, which indicates that when θ_3 and M_3 are constant there is an inverse relationship between the soil temperature at six inches and the air temperature three hours earlier. This result was unexpected and must have occurred because the air temperature has already exerted an effect upon the three inch

Table 19. Partial regression coefficients and their standard errors for the regression of the six inch soil temperature θ_6 under grass using T_3, M_6, and θ_3 as independent variables

Season	Statistic	Variable T_3	M_6	θ_3
Winter	Regression coefficient	-.066***	.000026***	.854***
	Standard error	.015	.0000051	.031
Spring	Regression coefficient	-.159***	.00025	1.098***
	Standard error	.027	.00030	.037
Summer	Regression coefficient	-.033	-.00000077***	.880***
	Standard error	.030	.000000030	.045
Fall	Regression coefficient	-.141***	-.0000012**	1.055***
	Standard error	.021	.00000049	.029

***Significant at the one per cent level.
**Significant at the five per cent level.

soil temperature. Two of the partial regression coefficients of Table 19 are insignificant and the corresponding variables were removed from the regression analysis. The multiple correlation coefficients shown in Table 20 were obtained from this analysis. Equations (26) through (29) give the

Table 20. Multiple correlation coefficients for the prediction of the six inch soil temperature θ_6 under grass using the indicated independent variables

Season	Independent variables	R	R^2
Winter	T_3, M_6, θ_3	.982	.9640
Spring	T_3, θ_3	.984	.9688
Summer	M_6, θ_3	.991	.9824
Fall	T_3, M_6, θ_3	.996	.9913

final relationships for the prediction of the six inch soil temperature under grass.

Winter: $\hat{\theta}_6 = .854\ \theta_3 + .000026M_6 - .066T_3 + 7.79$ (26)

Spring: $\hat{\theta}_6 = 1.088\ \theta_3 - .015T_3 - 7.32$ (27)

Summer: $\hat{\theta}_6 = .840\ \theta_3 - .000000079M_3 + 9.72$ (28)

Fall: $\hat{\theta}_6 = 1.055\ \theta_3 - .0000012M_6 - .182T_3 + 4.59$ (29)

2. Prediction analysis under fallow cover

The prediction model for the six inch soil temperature under fallow is similar to that for the temperature under grass. In this analysis, the fallow three inch soil temperature θ_3' and the fallow six inch soil moisture M_6' are used for independent variables instead of the corresponding values for the grass cover.

The correlation coefficients for the analysis are shown in Table 21. Except for the soil moisture resistance during fall, all independent variables were significantly correlated with the six inch fallow soil temperature. The analysis produced the multiple correlation coefficients listed in

Table 21. Simple correlation coefficients used in relating the six inch soil temperature θ_6' under fallow with T_3, M_6', θ_3'

Season	Variable	Variable		
		T_3	M_6'	θ_3'
Winter	θ_6'	.626**	-.595**	.946**
	T_3		-.404**	.777**
	M_6'			-.582**
Spring	θ_6'	.812**	-.440**	.952**
	T_3		-.157	.896**
	M_3'			-.252*
Summer	θ_6'	.841**	.689**	.964**
	T_3		.491**	.888**
	M_6'			.650**
Fall	θ_6'	.904**	-.017	.986**
	T_3		.101	.946**
	M_6'			.062

**Significant at the one per cent level.
*Significant at the five per cent level.

Table 22. These coefficients were slightly smaller than the corresponding coefficients for the grass cover.

The partial regression coefficients obtained in this analysis are presented in Table 23, along with their corres-

Table 22. Multiple correlation coefficients and standard errors of estimate for relating the six inch soil temperature θ_6' under fallow to T_3, M_6', and θ_3'

Season	R	R^2	Standard error of estimate
Winter	.962	.9253	1.57
Spring	.976	.9527	2.06
Summer	.968	.9365	1.57
Fall	.993	.9858	1.38

ponding standard erros. As in the case of the six inch soil temperature under grass the partial regression coefficients for T_3 are negative. The only statistically non-significant partial regression coefficients were those for M_6' during winter and T_3 during summer. Using the remaining variables a new analysis was conducted for each season and the final multiple correlation coefficients are presented in Table 24. The appropriate prediction relationships are found in equations (30) through (33).

Table 23. Partial regression coefficients and their standard errors for the regression of the six inch soil temperature θ_6' under fallow using T_3, M_6', and θ_3' as independent variables

Season	Statistic	T_3	M_6'	θ_3'
Winter	Regression coefficient	-.114***	-.0019	.836***
	Standard error	.025	.0018	.049
Spring	Regression coefficient	-.094**	-.013***	.876***
	Standard error	.045	.0019	.057
Summer	Regression coefficient	-.020	.0032***	.749***
	Standard error	.044	.0011	.057
Fall	Regression coefficient	-.182***	-.0053***	1.025***
	Standard error	.034	.0012	.040

***Significant at the one per cent level.
**Significant at the five per cent level.

Winter: $$\hat{\theta}_6' = .860\,\theta_3' - .116T_3 + 9.89 \qquad (30)$$

Spring: $$\hat{\theta}_6' = .876\,\theta_3' - .013M_3' - .094T_3 + 19.40 \qquad (31)$$

Summer: $$\hat{\theta}_6' = .726\,\theta_3' - .0035M_3' + 15.19 \qquad (32)$$

Fall: $$\hat{\theta}_6' = 1.025\,\theta_3' - .0053M_6' - .182T_3 + 13.42 \qquad (33)$$

Table 24. Multiple correlation coefficients for predicting the six inch soil temperature under fallow using the indicated independent variables

Season	Independent variables	R	R^2
Winter	T_3, θ'_3	.961	.9243
Spring	T_3, M'_6, θ'_3	.976	.9527
Summer	M'_6 θ'_3	.968	.9364
Fall	T_3, M'_6, θ'_3	.993	.9858

C. Prediction of the Twelve Inch Soil Temperature

1. Prediction analysis under grass cover

According to the suggested hypothesis the twelve inch soil temperature θ_{12} under grass may be predicted by the use of the air temperature T_4 at 7:30 a.m. on the day of the soil temperature observation, by the soil moisture M_{12} at twelve inches under the grass cover, and by the six inch soil temperature θ_6 under grass.

The correlation coefficients which show the interdependence of all variables are shown in Table 25. When these variables were combined into the regression analysis, the multiple correlation coefficients found in Table 26 were obtained. These multiple correlation coefficients are slightly smaller than

Table 25. Simple correlation coefficients used in relating the twelve inch soil temperature θ_{12} under grass with T_4, M_{12}, and θ_6

Season	Variable	Variable T_4	M_{12}	θ_6
Winter	θ_{12}	.467**	.107	.902**
	T_4		-.114	.682**
	M_{12}			-.103
Spring	θ_{12}	.818**	-.782**	.973**
	T_4		-.595**	.872**
	M_{12}			.752**
Summer	θ_{12}	.696**	.413	.918**
	T_4		.405**	.802**
	M_{12}			.458**
Fall	θ_{12}	.890**	-.038	.988**
	T_4		.006	.915**
	M_{12}			-.032

**Significant at the one per cent level.
*Significant at the five per cent level.

the corresponding coefficients for the six inch analysis, but they are larger than those found in the three inch analysis under a grass cover.

In Table 27 are listed the partial regression coefficients obtained from the regression analysis. For the summer and fall

Table 26. Multiple correlation coefficients and the standard errors of estimate for relating the twelve inch soil temperature θ_{12} under grass to T_4, M_{12}, and θ_6

Season	R	R^2	Standard error of estimate
Winter	.938	.8806	1.29
Spring	.978	.9562	1.52
Summer	.920	.8468	1.46
Fall	.986	.9722	1.44

Table 27. Partial regression coefficients with their standard errors for the regression of twelve inch soil temperature θ_{12} under grass using T_4, M_{12}, and θ_6

Spring	Statistic	Variable		
		T_4	M_{12}	θ_6
Winter	Regression coefficient	-.079***	.0000048**	.803***
	Standard error	.019	.00000077	.046
Spring	Regression coefficient	-.062*	-.0014**	.902***
	Standard error	.035	.00060	.064
Summer	Regression coefficient	-.065	-.000000093	.771***
	Standard error	.042	.00000090	.056
Fall	Regression coefficient	-.043	-.00000039	.871***
	Standard error	.033	.0000019	.045

***Significant at the one per cent level.
**Significant at the five per cent level.
*Significant at the ten per cent level.

seasons, only the regression coefficients for θ_6 test significantly different from zero. When the remaining variables were removed, the square of simple correlation coefficients for θ_6, as shown in Table 28, becomes the estimate of the variation explained by the regression analysis. A comparison

Table 28. Multiple correlation coefficients for predicting the twelve inch temperature under grass using the indicated independent variables

Season	Independent variables	R	R^2
Winter	T_4, M_{12}, θ_6	.938	.8806
Spring	T_4, M_{12}, θ_6	.978	.9562
Summer	θ_6	.918	.8423
Fall	θ_6	.986	.9716

of these values with those of Table 26 reveals that the amount of variation explained by regression was reduced by 0.4 per cent in summer and less than 0.01 per cent in fall with the removal of these variables. During winter and spring the partial regression equations for all of the independent variables tested significant. Equations (34) through (37) give the final regression equations for each season.

Winter: $\hat{\theta}_{12} = .803\,\theta_6 + .0000048M_{12} - .079T_4 + 10.36$ (34)

Spring: $\hat{\theta}_{12} = .902\,\theta_6 - .0014M_{12} - .062T_4 + 7.20$ (35)

Summer: $\hat{\theta}_{12} = .701\ \theta_6 + 19.37$ (36)

Fall: $\hat{\theta}_{12} = .819\ \theta_6 + 10.22$ (37)

2. Prediction analysis under fallow cover

The model for the prediction analysis of the twelve inch fallow temperature is similar to that for the twelve inch grass temperature. The difference being that for the fallow twelve inch temperature the fallow moisture resistance M'_{12} and six inch temperature θ'_6 were employed. The correlation coefficients for the variables used in this analysis are listed in Table 29, with the same type of interactions between variables noted as in the preceding analysis. The multiple correlation coefficients obtained are shown in Table 30. These correlation coefficients are of about the same magnitude as those obtained in the analyses for grass cover.

The partial regression coefficients obtained are listed in Table 31. In the winter season all of the partial regression coefficients were significantly different from zero, while for the spring and summer seasons the coefficients for T_4 were not significant. In fall as in the case of the grass cover, only the six inch soil temperature provided a partial regression coefficient significantly different from zero.

The regression analysis, which was based on the variables

Table 29. Simple correlation coefficients used in relating the twelve inch soil temperature θ'_{12} under fallow with T_4, M'_{12}, θ'_6

Season	Variable	Variable T_4	M'_{12}	θ'_6
Winter	θ'_{12}	.473**	-.205	.903**
	T_4		-.196	.643**
	M'_{12}			-.373**
Spring	θ'_{12}	.834**	-.777**	.948**
	T_4		-.546**	.898**
	M'_{12}			-.646**
Summer	θ'_{12}	.703**	.700**	.949**
	T_4		.185	.774**
	M'_{12}			.628**
Fall	θ'_{12}	.905**	-.454**	.981**
	T_4		.317*	.933**
	M'_{12}			.441**

**Significant at the one per cent level.
*Significant at the five per cent level.

Table 30. Multiple correlation coefficients and standard errors of estimate for relating the twelve inch soil temperature θ'_{12} with T_4, M'_{12}, and θ'_6

Season	R	R^2	Standard error of estimate
Winter	.926	.8579	1.49
Spring	.972	.9442	1.97
Summer	.959	.9202	1.72
Fall	.982	.9647	1.79

Table 31. Partial regression coefficients and their standard errors obtained when the twelve inch fallow soil temperature was related to T_4, M'_{12}, and θ'_6

Season	Statistic	Variable T_4	M'_{12}	θ'_6
Winter	Regression coefficient	-.063***	.0060***	.752***
	Standard error	.021	.0020	.048
Spring	Regression coefficient	-.021	-.013***	.700***
	Standard error	.042	.0019	.069
Summer	Regression coefficient	.062	.0041***	.592***
	Standard error	.047	.00097	.060
Fall	Regression coefficient	.045	-.0014	.849***
	Standard error	.049	.0022	.062

***Significant at the one per cent level.

with significant partial regression coefficients, yielded the multiple correlation coefficients listed in Table 32. From this analysis the regression relationships found in equations (38) through (41) were obtained.

Winter: $$\hat{\theta}'_{12} = .752\ \theta'_6 + .0060M'_{12} - .062T_4 + 5.24 \qquad (38)$$

Spring: $$\hat{\theta}'_{12} = .672\ \theta'_6 - .013M'_{12} + 25.24 \qquad (39)$$

Summer: $$\hat{\theta}'_{12} = .660\ \theta'_6 + .003M'_{12} + 19.32 \qquad (40)$$

Fall: $$\hat{\theta}'_{12} = .805\ \theta'_6 + 7.56 \qquad (41)$$

Table 32. Multiple correlation coefficients relating the twelve inch soil temperature θ'_{12} under fallow soil with the indicated independent variables

Season	Independent variable	R	R^2
Winter	T_4, M_{12}, θ_6	.926	.8579
Spring	M'_{12}, θ'_6	.972	.9448
Summer	M'_{12}, θ'_6	.958	.9186
Fall	θ'_6	.981	.9633

D. Prediction of the Twenty-four Inch Soil Temperature

1. Prediction analysis under grass cover

The model for this prediction analysis suggests that the twenty-four inch temperature under a grass cover may be predicted from the air temperature T_5 at 9:30 a.m. the previous day, the twenty-four inch soil moisture M_{24} under grass, and the twelve inch soil temperature θ_{12} under grass.

The computed correlation coefficients, which measure the relationship between variables, are shown in Table 33. Using these simple correlation coefficients, the multiple regression coefficients listed in Table 34 were obtained. The multiple coefficients are approximately the same size as those found for the twelve inch temperature, with the coefficients for winter and summer being less than those for fall and spring.

The partial regression coefficients found in this analysis are listed in Table 35. Except for the partial regression coefficient for soil moisture resistance in fall, all coefficients tested significantly different from zero.

Table 33. Simple correlation coefficients relating the twenty-four inch soil temperature θ_{24} under grass to T_5, M_{24}, and θ_{12}

Season	Variable	T_5	M_{24}	θ_{12}
Winter	θ_{24}	.264*	.310*	.808**
	T_5		-.332**	.691**
	M_{24}			-.016
Spring	θ_{24}	.774**	-.809**	.969**
	T_5		-.540**	.870**
	M_{24}			-.748**
Summer	θ_{24}	.490**	.404	.870**
	T_5		.016	.713**
	M_{24}			.188
Fall	θ_{24}	.843**	-.309*	.978**
	T_5		-.237	.914**
	M_{24}			-.303*

**Significant at the one per cent level.
*Significant at the five per cent level.

Table 34. Multiple regression coefficients obtained in relating the twenty-four inch soil temperature θ_{24} under grass to T_5, M_{24}, and θ_{12}

Season	R	R^2	Standard error of estimate
Winter	.919	.8445	1.27
Spring	.983	.9660	1.30
Summer	.915	.8375	1.56
Fall	.987	.9740	1.05

Table 35. Partial regression coefficients and their standard errors of estimate obtained for relating the twenty-four inch soil temperature θ_{24} under grass to T_5, M_{24}, and θ_{12}

Season	Statistic	Variable T_5	M_{24}	θ_{12}
Winter	Regression coefficient	-.102***	.000014***	.974***
	Standard error	.018	.0000046	.066
Spring	Regression coefficient	-.101***	-.000044***	.860***
	Standard error	.024	.000013	.054
Summer	Regression coefficient	-.113***	.000038***	1.016***
	Standard error	.033	.0000076	.067
Fall	Regression coefficient	-.136***	-.000000041	.953***
	Standard error	.023	.0000095	.040

***Significant at the one per cent level.

The soil moisture resistance was removed as a variable from the fall analysis. The resulting multiple correlation coefficient is shown in Table 36. The prediction equations for the twenty-four inch temperature under grass are shown in equations (42) through (45).

Table 36. Multiple correlation coefficients obtained in relating the twenty-four inch soil temperature θ_{24} under grass with the indicated independent variables

Season	Independent variables	R	R^2
Winter	T_5, M_{24}, θ_{12}	.919	.8445
Spring	T_5, M_{24}, θ_{12}	.983	.9660
Summer	T_5, M_{24}, θ_{12}	.915	.8375
Fall	T_5, θ_{12}	.986	.9720

Winter: $\hat{\theta}_{24} = .974\,\theta_{12} + .000014M_{24} - .102T_5 + 6.69$ (42)

Spring: $\hat{\theta}_{24} = .860\,\theta_{12} + .000044M_{24} - .101T_5 + 13.04$ (43)

Summer: $\hat{\theta}_{24} = 1.016\,\theta_{12} + .000038M_{24} - .113T_5 + 3.52$ (44)

Fall: $\hat{\theta}_{24} = .974\,\theta_{12} - .162T_5 + 13.14$ (45)

2. <u>Prediction analysis under fallow cover</u>

The model suggested for this analysis utilizes T_5, M'_{24}, and θ'_{12} as independent variables. The simple correlation coefficients for this analysis are presented in Table 37, while the multiple correlation coefficients obtained in the analysis are given in Table 38. These multiple correlation coefficients are about the same size as those obtained in the grass analysis shown in Table 34, except that in this case the coefficient for the summer season is greater.

Table 37. Simple correlation coefficients for relating twenty-four inch soil temperature θ'_{24} under fallow to T_5, M'_{24}, and θ'_{12}

Season	Variable	Variable T_5	M'_{24}	θ'_{12}
Winter	θ'_{24}	.335**	.065	.828**
	T_5		-.444**	.672**
	M'_{24}			-.251*
Spring	θ'_{24}	.784**	-.846**	.959**
	T_5		-.575**	.882**
	M'_{24}			-.748**
Summer	θ'_{24}	.527**	.774**	.920**
	T_5		.185	.743**
	M'_{24}			.582**
Fall	θ'_{24}	.868**	-.194	.974**
	T_5		-.219	.933**
	M'_{24}			-.200

**Significant at the one per cent level.
*Significant at the five per cent level.

Table 38. Multiple correlation coefficients and the errors of estimate obtained for relating the twenty-four inch temperature θ'_{24} under fallow with T_5, M'_{24}, and θ_{12}

Season	R	R^2	Standard error of estimate
Winter	.900	.8095	1.44
Spring	.983	.9655	1.30
Summer	.971	.9421	.98
Fall	.982	.9649	1.36

The partial regression coefficients for this analysis are listed in Table 39. As was the case of the twenty-four inch grass temperature, only the coefficient for the fall moisture resistance failed to test statistically significant. This variable was removed from the analysis, and the multiple

Table 39. Partial regression coefficients and their standard errors obtained in relating the twenty-four inch temperature θ'_{24} under fallow to T_5, M'_{24}, and θ'_{12}

Season	Statistic	Variable T_5	M'_{24}	θ'_{12}
Winter	Regression coefficient	-.069***	.0077***	.900***
	Standard error	.020	.0025	.066
Spring	Regression coefficient	-.081***	-.014***	.778***
	Standard error	.025	.0021	.056
Summer	Regression coefficient	-.105***	.012***	.738***
	Standard error	.024	.0015	.044
Fall	Regression coefficient	-.152***	-.0010	.962***
	Standard error	.033	.0025	.051

***Significant at the one per cent level.

correlation coefficient as shown in Table 40 was computed. These calculations provided the prediction relationships listed in equations (46) through (49).

Winter: $\hat{\theta}'_{24} = .900\,\theta'_{12} + .0077M'_{24} - .069T_5 - .06$ (46)

Spring: $\hat{\theta}'_{24} = .778\,\theta'_{12} - .014M'_{24} - .081T_5 + 24.83$ (47)

Summer: $\hat{\theta}'_{24} = .738\,\theta'_{12} + .012M'_{24} - .104T_5 + 17.09$ (48)

Fall: $\hat{\theta}'_{24} = .989\,\theta'_{12} - .176T_5 + 13.01$ (49)

Table 40. Multiple correlation coefficients relating the twenty-four inch soil temperature θ'_{24} under fallow with the indicated independent variables

Season	Independent variables	R	R^2
Winter	T_5, M'_{24}, θ'_{12}	.900	.8095
Spring	T_5, M'_{24}, θ'_{12}	.983	.9655
Summer	T_5, M'_{24}, θ'_{12}	.971	.9421
Fall	T_5, θ'_{12}	.981	.9629

V. DISCUSSION

A. Variation in the Partial Regression Coefficients of the Prediction Equations

1. The analysis for the three inch soil temperature

a. The analysis which employed T_u and T_l. The regression equations which utilized T_u and T_l as independent variables are shown in equations (10) through (13) for the grass cover and in equations (18) through (21) for the fallow cover. These equations were obtained by a multiple regression analysis which was based on the correlation coefficients of Tables 1 and 9.

In every season and for each type of cover the partial regression coefficients associated with T_u and T_l tested significantly different from zero. Since these coefficients were all positive, increases in T_u and T_l resulted in rises of the three inch soil temperature. The coefficients for T_u varied from 0.08 in the winter to 0.20 in the fall. Each degree increase in the upstream air temperature resulted in a 0.1° to 0.2° F. increase in the three inch soil temperature. The partial regression coefficients for T_l were 3.5 to four times greater than those for T_u varying from 0.32 to 0.46. A degree change in the previous air temperatures produced

0.3° to 0.5° F. change in the three inch soil temperature.

The partial regression coefficients for S were all statistically significant and positive. The coefficient for the grass analysis in winter was smallest, when a 100 calorie change in solar energy yielded a 1.2° F. change in the three inch soil temperature; and it was largest for the fall grass cover, when a 100 calorie change in energy resulted in a 2.9° F. temperature change.

In all except the winter season the partial regression coefficients for C were positive. Night cloudiness prevented the nocturnal terrestrial radiation from escaping through the atmosphere. This condition increased the amount of energy available for warming the soil. In winter the partial regression coefficients associated with C for the grass and fallow covers failed to reach significance. The freezing of the soil surface during the hours of darkness altered the heat-content-temperature relationship and produced a small negative partial regression coefficient for C. The partial regression coefficients associated with C during spring and fall under fallow soil failed to reach significance. This insignificance is difficult to explain, since these coefficients were significant when analysis was conducted for the grass cover. The smallest significant partial regression coefficient for C was 0.224 in the case of the summer fallow analysis, indicating that completely overcast night sky resulted in a 2.2° F. higher three inch soil temperature under fallow conditions on the following afternoon. The largest partial regression coefficient associated with the C variable was 0.404 for the spring season under grass cover. A complete cloud cover increased the soil temperature the following afternoon by 4.0° F. above the temperature for a clear night.

The partial regression coefficients for W obtained in the analysis were negative for all seasons except winter. High wind velocities provided a means for mixing the air in the lower atmosphere and for the transport of heat from the surface. This effect was most pronounced during summer when more heat was available at the surface, and the highest partial regression coefficients were found for this season. The average wind velocity produced partial regression coefficients which tested significantly different from zero during the summer season for both covers and during the spring season for the grass cover. During the cooler portion of the year wind was not sufficiently important to produce significant partial regression coefficients. An average daily wind of ten miles per hour in summer reduced the 5:00 p.m. soil temperature at the three inch depth 4.0° F. under grass and 5.0° F. under fallow from the temperature which would have resulted from a near calm condition.

The partial regression coefficients for M_3 and M_3' were not all of the same sign, but the significant coefficients were all positive. Drier soil, as indicated by higher soil moisture resistances, resulted in higher soil temperatures, due to the higher specific heat of the soil system caused by the addition of water. During winter and spring the partial regression coefficients associated with M_3 and M_3' were not significantly different from zero, because of the low day to day variability in the soil moisture during these seasons. In summer and fall, when the day to day variability in soil moisture was greater, the partial regression coefficients were significant. The average soil moisture resistance under grass during the summer and spring seasons averaged 400 and 100 times greater than the soil moisture resistances under fallow conditions. This difference resulted in partial regression coefficients 4000 times greater under fallow cover than under grass.

b. <u>The analysis which employed T_2</u>. The prediction equations obtained from this analysis are shown in equations (14) through (17) for the grass cover, while equations (22) through (25) give the relationships for the fallow cover. These regression equations are like those discussed earlier, except that in this analysis T_2 has replaced T_u and T_1.

The regression coefficients associated with T_2 are much larger than those resulting from either T_u and T_1. These coefficients are positive and all are statistically significant. The highest values for these partial regression coefficients were found for the spring and fall seasons under fallow soil. During these seasons a degree change in T_2 was associated with a 0.7° F. change in the fallow three inch soil temperature. The lowest partial regression coefficient was found in winter under a grass cover when one degree change in T_2 resulted in a 0.4° F. change in the grass three inch soil temperature.

The partial regression coefficients for S were slightly smaller than those of the previous analysis. They were all positive, and all tested significantly different from zero. The temperature change resulting from a 100 calorie change in the daily solar energy was about 2° F. during the fall, and nearly 1° F. for the remainder of the year.

The variable C did not greatly differ in its contribution to the three inch soil temperature from that of the preceding analysis. The chief difference was that the partial regression coefficient for the fallow three inch temperature during summer did not reach significance as it had before. An overcast night sky during spring raised the following afternoon's soil temperature at three inches under a grass cover by 4° F. during the spring seasons. The smallest significant coefficient was reported during summer under a grass cover where an overcast night sky increased the three inch soil temperature by 2.5° F. on the following afternoon.

Considerable differences were noted in partial regression coefficients associated with the average wind velocity when this analysis was compared with the preceding one. The partial regression coefficient found for the grass temperature during winter was significant and positive. During spring, strong wind speeds result in heat transfer to the earth surface from the atmosphere, since higher soil temperatures are associated with higher wind speeds. Another significant partial regression coefficient associated with W was obtained for the grass cover during summer. This value was negative, indicating the loss of heat from the surface as a result of the higher wind speeds.

There is very little difference in the size of the partial regression coefficients for M_3 and M_3'. For the first time the coefficients for M_3' during winter and spring are significant. The partial regression coefficient for the winter season is even negative indicating that the soil temperature increased with decreasing soil moisture resistances, or increasing soil moisture. This relationship was due to the increase in thermal conductivity associated with the increased moisture content and to the greater conductivity of frozen soil.

2. The analysis for the deeper soil depths

a. The prediction equations for the six inch depth.

Equations (26) through (29) are the prediction equations for the temperature of the soil under a grass cover at the six inch depth, while equations (30) through (33) provide the relationships for the fallow cover.

The three inch soil temperature provides larger partial regression coefficients than either of the other independent variables. The magnitudes of the partial regression coefficients varied with the season and cover. In summer, under a fallow soil, a one degree change in temperature at the three inch depth resulted in a 0.15° F. temperature change at six inches, while during spring under grass a soil temperature change of one degree at the three inch depth resulted in a 1.1° F. change at six inches. All partial regression coefficients associated with the three inch soil temperature were statistically significant and positive.

The partial regression coefficients associated with the antecedent temperature T_3 were small but negative. This leads to the apparent paradox that cold air temperatures are associated with warm soil temperatures. Examination of Tables 17 and 21 shows that the simple correlation coefficients expressing the relationship between the three inch soil temperature and T_3 are positive, and that T_3 and the six inch soil temperature are directly related. The negative partial regression coefficients for T_3 occurred because the effect of air temperature was greater at three inches than at six inches, and the effect was felt earlier at this shallower level. These negative coefficients correct for the greater effect exhibited by the air temperature on the three inch temperature than on the six inch temperature. The partial regression coefficients were larger during the fall than during the other seasons with the coefficients for summer failing to reach significance. Even in the fall a change of one degree in T_3 will only change the six inch soil temperature about .2^{o} F.

The six inch soil moisture resistance, at constant antecedent air temperature and three inch soil temperature, exhibits an erratic effect upon the six inch soil temperature. All of partial regression coefficients, except two tested significantly different from zero, but some are positive while others are negative. It is impossible to explain the variation in the signs of these regression coefficients, but it is probably due to the correlation between the soil moisture resistance and other variables, and to the complicated relationship between soil moisture and soil temperature.

b. The prediction equations for the twelve inch depth. In equations (34) through (41) are shown the relationships for the prediction of the twelve inch soil temperatures. In these equations the six inch soil temperature exhibits a dominant effect on the twelve inch temperature. In three cases the six inch soil temperature is the only independent variable with a significant partial regression coefficient. This does not mean that the other independent variables are not related to the twelve inch soil temperature. The failure of the other variables to provide significant partial regression coefficients was due to the high correlation between θ_6 and the other independent variables, and between θ_6 and the twelve inch soil temperature. During the fall season 96 per cent of the variation in the twelve inch fallow soil temperature was explained by the six inch temperature. This did not leave much variation to be explained by other independent variables. The partial regression coefficients associated with θ_6 indicate that each degree of change in the six inch soil temperature is associated with a .6° to .9° F. change in the twelve inch temperature.

The partial regression coefficients for T_4 are negative. The explanation for this contradiction to circumstance is the same as for T_3. Since the simple correlation coefficients associated with T_4 are positive, the negative partial regression coefficients resulted from the inter-relationships between the independent variables. The partial regression coefficients were statistically significant during the winter season for both covers and during the spring season for the grass cover.

Soil moisture performed as a predictor in an erratic manner. All of the significant partial regression coefficients were positive, except during the spring when negative values were obtained. There were considerable variations in the size of the partial regression coefficients, with the season and cover with highest average soil moisture resistance producing the smallest coefficient.

c. The prediction equations for the twenty-four inch depth. Equations (42) through (49) give the prediction relationships for the twenty-four inch soil temperature. These equations are quite similar to those for the six and twelve inch depths. The soil temperature at the shallower depth was the best predictor. The antecedent temperature, T_5, yielded small and negative partial regression coefficients, and all tested statistically significant. The effect of M_{24} and M'_{24} was less erratic than in the previous analysis, but one of the significant partial regression coefficients was negative.

B. Removal of Variables with Insignificant Partial Regression Coefficients

1. Criterion for the removal of a variable

The square of the correlation coefficient defines the amount of the dependent variable's variation explained by the regression analysis. The size of the correlation coefficient will depend upon the number of independent variables employed. Increasing the number of independent variables will result in an increase in the size of the correlation coefficient, while fewer independent variables will cause a decrease in the correlation coefficient. Independent variables which reduce the portion of explained variation an inconsequential amount are often removed from the analysis. This removal reduces the labor required for the evaluation of the prediction equation, and it assists in the emphasis of the importance of the remaining independent variables.

In these analyses, it was the adopted practice to remove all independent variables which failed to produce a partial regression coefficient statistically significant at the 90 per cent level. This practice reduced the amount of explained variation, but it also reduced the number of independent variables.

2. <u>The amount of decrease in the explained variation by the removal of variables</u>

The multiple correlation coefficients obtained before and after the insignificant independent variables had been removed were reported earlier. From Table 2 it is noted that 69.94 per cent of the variation in θ_3 was explained by the regression analysis employing T_u, T_1, S, C, W, and M_3 as independent variables. Table 4 indicates that the amount of explained variation was reduced by only .51 per cent, when C, W, and M_3 were removed from the analysis.

In nearly 45 per cent of the cases, the removal of the insignificant independent variables did not reduce the amount of explained variation by as much as 0.01 per cent. In 70 per cent of the cases the reduction in the explained variation was less than 0.25 per cent. These percentages include the cases when all of the independent variables produced significant partial regression coefficients. A comparison of Tables 10 and 12 shows the largest reduction in the amount of explained variation by the removal of variables. The removal of C, W, and M_3' as independent variables, reduced the amount of variation explained by regression by 2.02 per cent in winter and 2.35 per cent in spring. Even for these cases the amount of reduction in the explained variation is not sufficient to make the inclusion of the discarded variables advisable.

C. The Between Season Variation in the Regression Equations

1. <u>The nature of the between season variation</u>

The regression analyses were conducted on a seasonal basis to reduce the overall variability in the data. This stratification made it possible to obtain higher correlation coefficients, since larger amounts of the variability could be explained. For every analysis there was one equation for each of the four seasons. These equations were the least squares solution based on the independent variables, and they provided a unique solution which was the "best" fit.

Significant differences between the seasonal equations are difficult to explain. If the equation for one season differs from that of the next season, the soil temperature prediction for days occurring near the end of the first season will be different from the soil temperature prediction for days at the beginning of the next season. This is unrealistic, since under identical meteorological and soil conditions the temperature estimates should be the same.

2. An example of comparisons of the prediction equations for different seasons

Equations (10) through (13) have been selected as an example for the comparison of the seasonal prediction equations. These equations are for the three inch soil temperature under a grass cover, and they employed T_u and T_l as predictors. They exhibited considerable season to season variation.

To test the possibility of extending the winter relationship into the spring season, the winter equation was applied to the coolest March days. Similarly, the spring equation was applied to the warmest February days. The results of this comparison in the application of the spring and winter equations are shown in Table 41. The winter equation underestimated the cool March soil temperatures, while the spring equation overestimated the same temperatures. The bias for the winter equation was less than the bias for the spring relationship. On cool spring days the winter relationship provided the best estimate of the three soil temperatures under grass. The winter equation also provided a smaller bias than the equation for spring when estimating warm February soil temperatures.

The spring equation was applied to the coolest June days in order to test its application in the summer season, while the summer equation was extended into the spring season by its application to the warmest May days. The results of these comparison are shown in Table 42. The summer equation estimates the cool spring soil temperature with a greater bias than obtained with the spring equation. The spring relationship estimated the cool June soil temperatures with a bias of same magnitude, but of an opposite sign, to that obtained from the use of the summer equation. Since the

Table 41. Comparison of the three inch soil temperatures predicted by the winter and spring equations for cool March and warm February days

	Equation for				Equation for		
Date	Winter	Spring	Actual	Date	Winter	Spring	Actual
2/ 4/54	43.4	44.8	44.7	3/ 1/54	44.4	48.1	35.4
2/ 5/54	45.5	48.5	44.8	3/ 4/54	39.4	37.8	34.7
2/ 9/54	47.3	52.3	49.1	3/ 5/54	40.2	42.2	35.2
2/10/54	47.7	52.0	47.8	3/ 7/54	46.7	51.7	49.6
2/15/54	53.5	61.0	54.7	3/ 8/54	49.0	55.8	49.6
2/16/54	49.5	51.2	49.8	3/11/54	46.9	49.9	48.4
2/17/54	46.4	51.5	49.6	3/15/54	43.0	44.1	43.9
2/18/54	48.2	52.4	50.4	3/16/54	45.4	49.9	48.8
2/22/54	48.5	54.2	48.5	3/17/54	47.0	54.0	49.7
2/24/54	45.7	50.7	48.7	3/19/54	46.0	51.5	48.0
2/24/54	41.2	45.1	48.2	3/29/54	45.7	50.4	42.9
				3/30/54	35.6	36.6	42.6
				3/31/54	43.9	49.7	49.1
Average	47.0	51.8	48.8		47.8	51.8	49.0

Table 42. Comparison of the three inch soil temperatures predicted by the spring and summer equations for warm May and cool June days

Date	Equation for Spring	Summer	Actual	Date	Equation for Spring	Summer	Actual
5/13/54	68.4	75.1	68.7	6/ 1/54	66.4	71.2	67.7
5/14/54	70.6	76.8	70.6	6/ 2/54	55.7	62.8	62.6
5/17/54	68.7	75.4	70.7	6/ 3/54	56.2	62.4	60.5
5/18/54	71.5	77.7	72.1	6/ 4/54	66.5	73.2	69.9
5/20/54	66.1	73.4	69.9	6/ 7/54	74.3	78.6	76.6
5/21/54	69.8	75.8	70.0	6/ 8/54	81.0	84.9	78.3
5/24/54	75.0	80.4	74.9	6/ 9/54	72.7	76.0	70.8
5/25/54	71.1	75.6	68.9	6/10/54	76.4	80.4	79.6
5/26/54	65.4	70.7	68.3	6/15/54	74.4	78.5	79.8
5/27/54	73.1	77.7	75.3				
5/28/54	66.3	71.2	69.4				
5/31/54	68.9	73.0	73.2				
Average	69.6	75.2	71.0		69.3	74.2	71.8

biases are of opposite sign, an improved estimate of the soils temperatures for these cool June days could have been obtained by averaging the temperatures predicted by the two equations.

Comparisons between the fall and summer equations were obtained by applying the fall equation to the coolest August days and the summer equation to the warmest September days. These comparisons are shown in Table 43. The fall equation was a poor predictor of the cool August soil temperatures. The soil temperatures on warm September days were estimated with identical bias by the two equations. This indicates the

Table 43. Comparison of the three inch soil temperatures predicted by the summer and fall equations for cool August and warm September days

	Equation for				Equation for		
Date	Summer	Fall	Actual	Date	Summer	Fall	Actual
8/10/53	81.0	78.1	80.5	9/ 1/53	90.0	91.6	89.6
8/11/53	77.0	71.4	80.6	9/ 2/53	86.6	87.4	85.5
8/12/53	83.2	77.0	80.6	9/ 9/53	77.2	78.3	76.0
8/15/53	81.8	76.6	79.0	9/10/53	80.1	80.7	78.5
8/16/53	73.6	64.2	74.4	9/11/53	81.3	79.9	79.3
8/17/53	75.0	68.2	76.1	9/17/53	75.8	75.8	76.9
8/18/53	80.6	76.7	77.1	9/19/53	79.4	75.2	77.4
8/19/53	78.9	74.2	78.1	9/28/53	75.4	76.9	79.3
8/20/53	80.1	75.4	78.3	9/29/53	72.7	78.6	79.0
8/21/53	79.2	73.5	77.9	9/30/53	77.4	76.8	77.0
8/22/53	81.8	77.7	80.2				
Average	79.3	73.9	78.4		80.1	80.1	79.8

close similarity between the prediction equations for the two seasons.

The comparisons of the winter and fall equations are shown in Table 44. The winter relationship was unable to predict the cool November temperature as well as the fall equation. The bias produced by the application of the fall equation to warm December days was of the same magnitude as bias associated with the winter equation. Since the bias for

Table 44. Comparison of the three inch soil temperatures predicted by the fall and winter equations for cool November and warm December days

	Equation for				Equation for		
Date	Fall	Winter	Actual	Date	Fall	Winter	Actual
11/ 5/53	52.4	45.9	50.4	12/ 1/53	53.2	45.4	48.0
11/ 6/53	46.2	41.4	48.4	12/ 3/53	51.0	44.4	54.5
11/ 9/53	49.3	43.2	49.3	12/ 4/53	53.9	47.4	45.8
11/23/53	46.9	41.7	48.2	12/ 7/53	45.1	41.1	46.5
11/24/53	51.8	45.6	47.3	12/ 8/53	53.3	46.3	48.5
11/25/53	39.8	39.3	42.5	12/10/53	46.6	40.3	43.0
11/27/53	47.4	43.2	44.3	12/11/53	42.9	41.4	41.8
11/28/53	46.2	40.2	43.1	12/21/53	49.0	44.3	46.1
11/30/53	50.1	43.2	47.9				
Average	47.8	42.6	46.8		49.4	43.8	46.8

the fall equation was of an opposite sign to that of the winter equation, the average of these two values would have provided a nearly unbiased estimate of the three inch soil temperature.

The comparisons shown here are for but one type of cover and depth. It seems reasonable that these comparisons are applicable to other analyses for the three inch soil temperature. The regression equations for the deeper levels did not show as great a season to season variation.

D. The Relationship between the Predicted and Observed Soil Temperatures

1. The three inch soil temperature

a. The winter predictions. The multiple correlation coefficients obtained for the winter analyses were smaller than the coefficients of any other season. During winter about 70 per cent of the variation in the three inch soil temperature was explained by the regression analysis. As a result of this large variation a wide scatter of points was obtained when the observed soil temperatures were plotted against the predicted soil temperatures. These data are shown in Figures 4 through 7.

One of the difficulties in estimating the winter soil

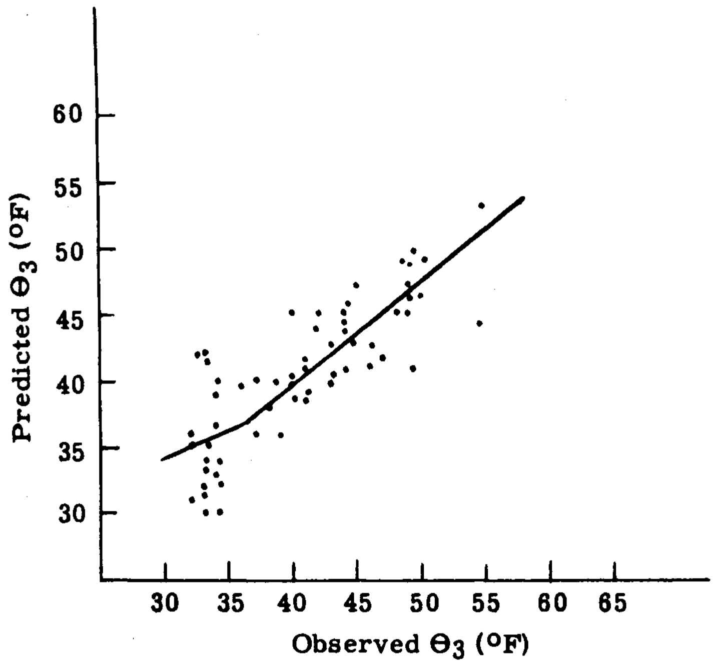

Figure 4. The relationship between the observed and the predicted Θ_3 for winter using T_u, T_1 and S as predictors.

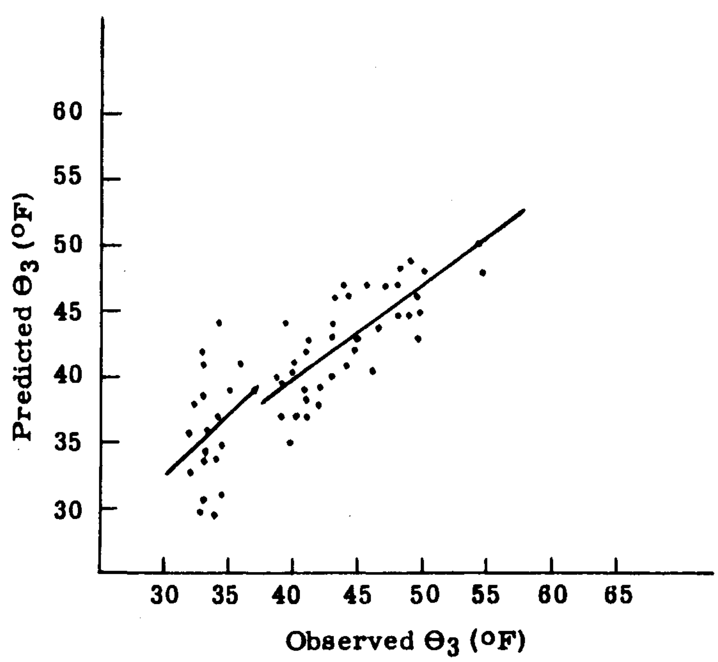

Figure 5. The relationship between the observed and the predicted Θ_3 for winter using T_2, S, and W as predictors.

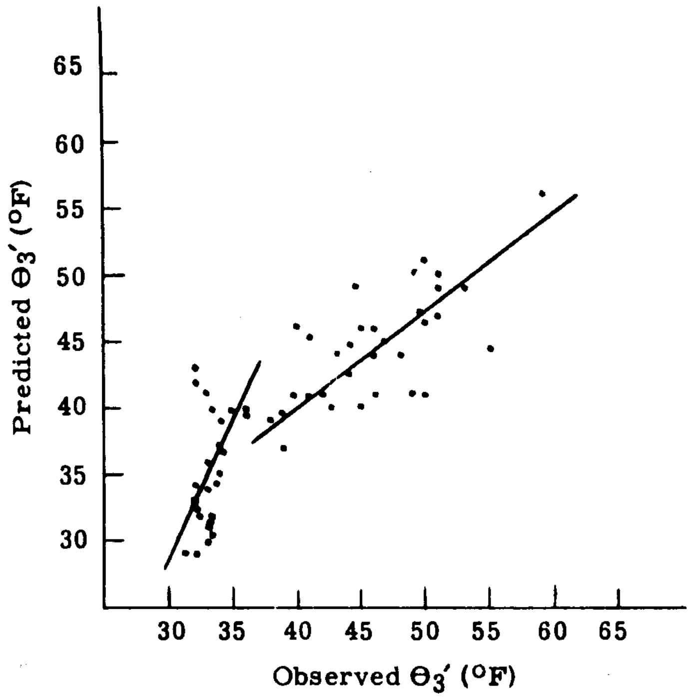

Figure 6. The relationship between the observed and the predicted Θ_3' for winter using T_u, T_1, and S as predictors.

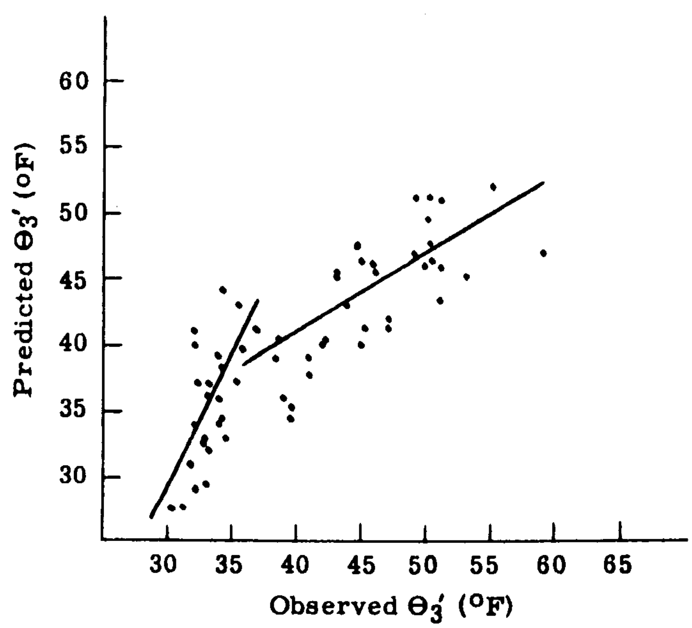

Figure 7. The relationship between the observed and the predicted Θ_3' for winter using T_2, S, W, and M_3' as predictors.

temperature is that the response is different at near freezing temperatures than at temperatures above freezing. This differential response is due to the heat of fusion associated with the change in state of water in the soil. Figures 4 through 7 show a different response at observed temperatures below 37° F. than at temperatures above 37° F. Soil with this low a temperature at 5:00 p.m. had been frozen earlier in the day.

The data in Figures 4 and 5 indicate that at near freezing temperatures a low correlation exists between the observed three inch grass temperatures and the predicted temperatures. These coefficients were not statistically significant, being equal to 0.114 for Figure 4 and 0.212 for Figure 8. Higher correlation coefficients were obtained for relating the observed to the predicted soil temperatures at observed temperatures above 37° F. For data in Figure 4 this correlation coefficient was 0.810, while the coefficient associated with Figure 5 was 0.745.

For fallow conditions the relationship between the observed and the predicted three inch soil temperatures were better than under the grass cover. These relationships are shown in Figure 6 and 7. The correlation coefficients between the observed and the predicted soil temperatures at observed temperatures below 37° F. were 0.516 for the data in Figure 6 and 0.616 for the data of Figure 7. At observed temperatures above 37^{o} F. the correlation coefficients became 0.720 in Figure 6 and 0.775 for Figure 7.

Figures 4 through 7 indicate that the equations for predicting the three inch temperature during winter should be adjusted. This adjustment is different for days when freezing interrupts the soil's normal heat economy than for days with above freezing temperatures. Since the correlation between the observed and the predicted temperatures remains low even after the adjustment, it is advisable to make further attempts at the modification of basic prediction equations.

There are two methods for predicting the three inch soil temperatures. The method which gives the smaller scatter of points in Figures 4 through 7, will yield the best estimate. Similarly, the method which produces the higher multiple correlation coefficient gives the better prediction. Examination of the figures and multiple correlation coefficients shows that T_u and T_l gave a slightly more precise estimate of the three inch winter soil temperatures than the analysis using only T_2.

b. <u>The predictions for the other seasons</u>. Presented in Figures 8 through 19 are the comparisons between the observed and the predicted three inch soil temperatures for the remaining seasons. On each chart is drawn the regression line which relates the observed to the predicted soil temperatures.

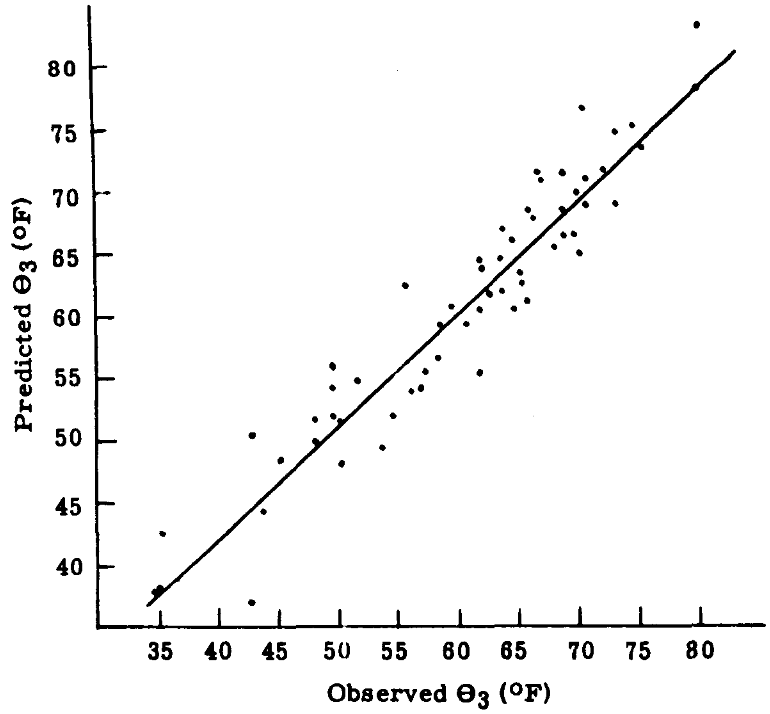

Figure 8. The relationship between the observed and the predicted Θ_3 for spring using T_u, T_1, S, C, and W as predictors.

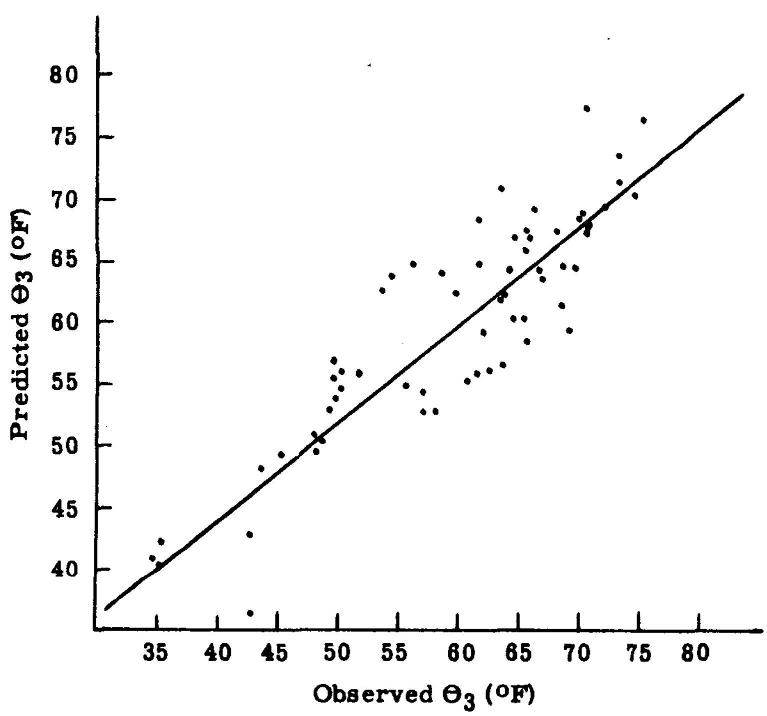

Figure 9. The relationship between the observed and the predicted Θ_3 for spring using T_2, S, and C as predictors.

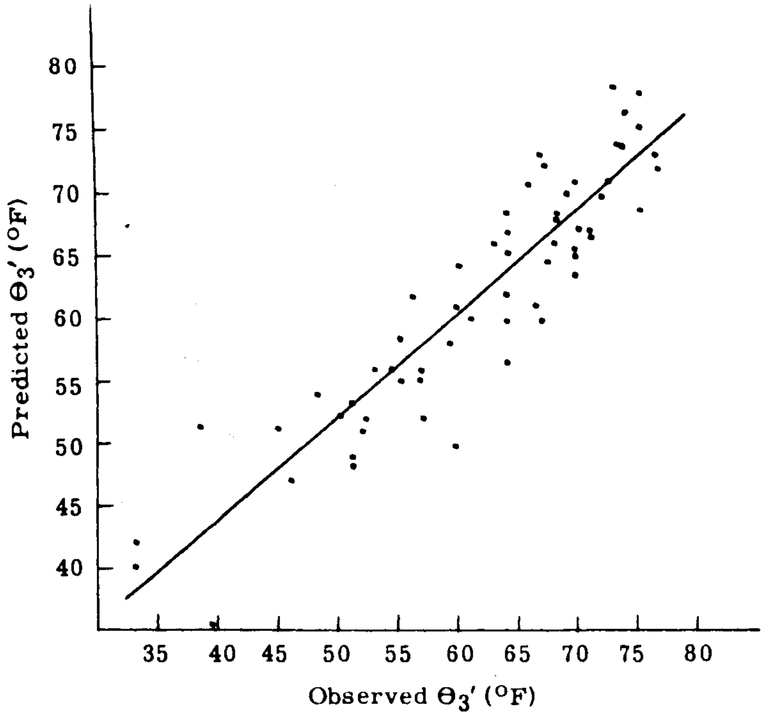

Figure 10. The relationship between the observed and the predicted Θ_3' for spring using T_u, T_1, and S as predictors.

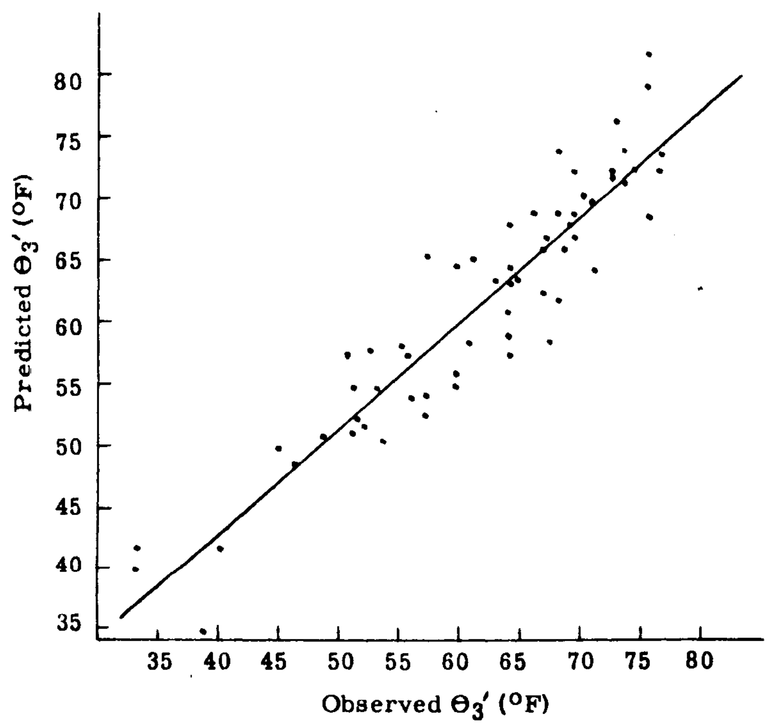

Figure 11. The relationship between the observed and the predicted Θ_3' for spring using T_2, S, C, and M_3' as predictors.

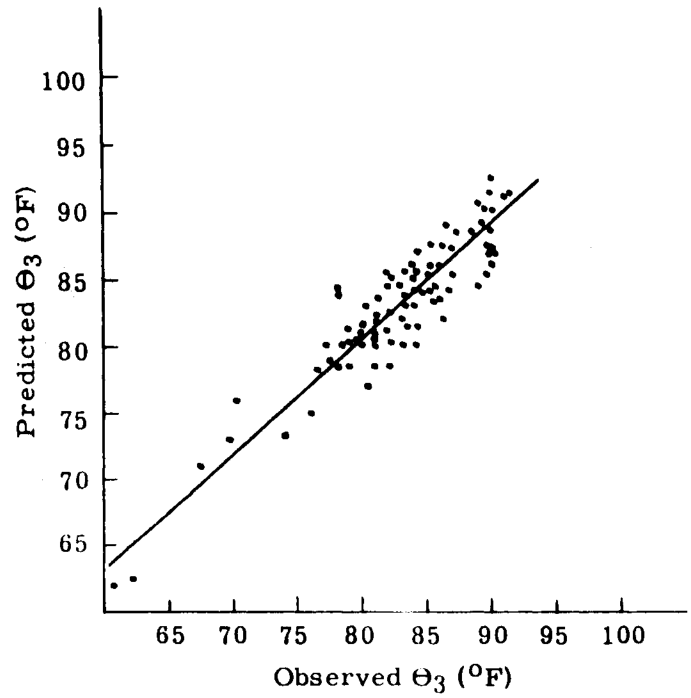

Figure 12. The relationship between the observed and the predicted Θ_3 for summer using T_u, T_1, S, C, W, and M_3 as predictors.

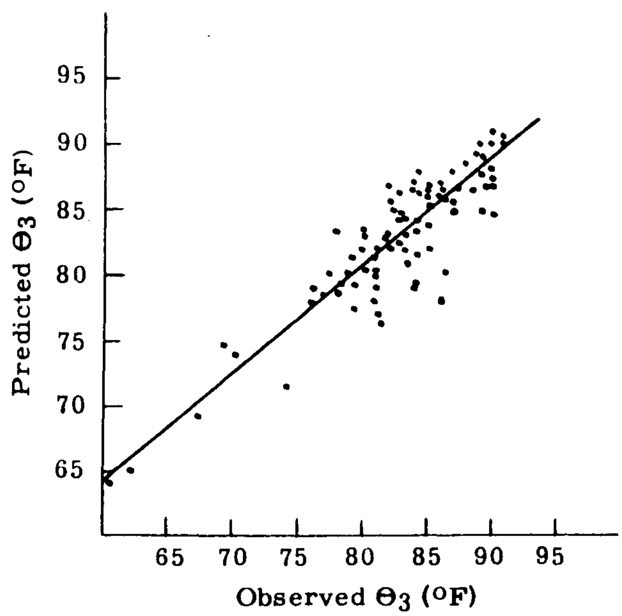

Figure 13. The relationship between the observed and the predicted Θ_3 for summer using T_2, S, C, W, and M_3 as predictors.

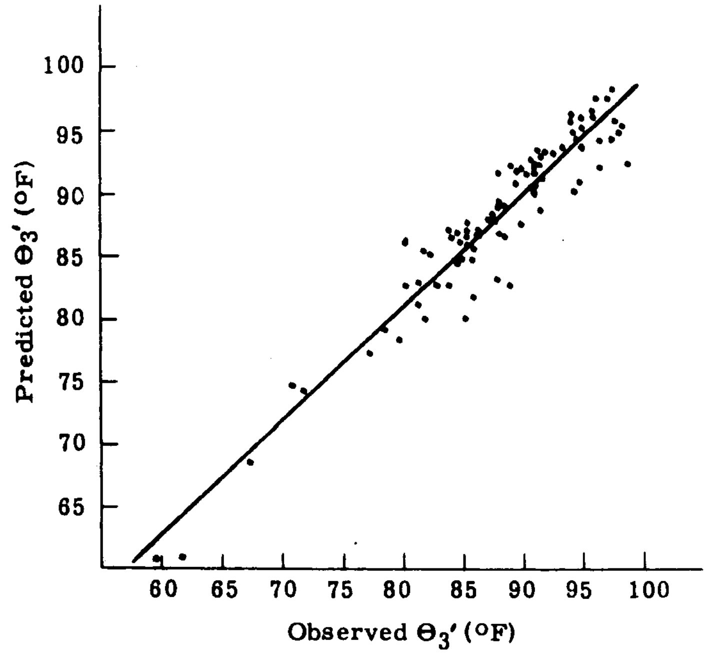

Figure 14. The relationship between the observed and the predicted Θ_3' for summer using T_u, T_1, S, C, W, and M_3' as predictors.

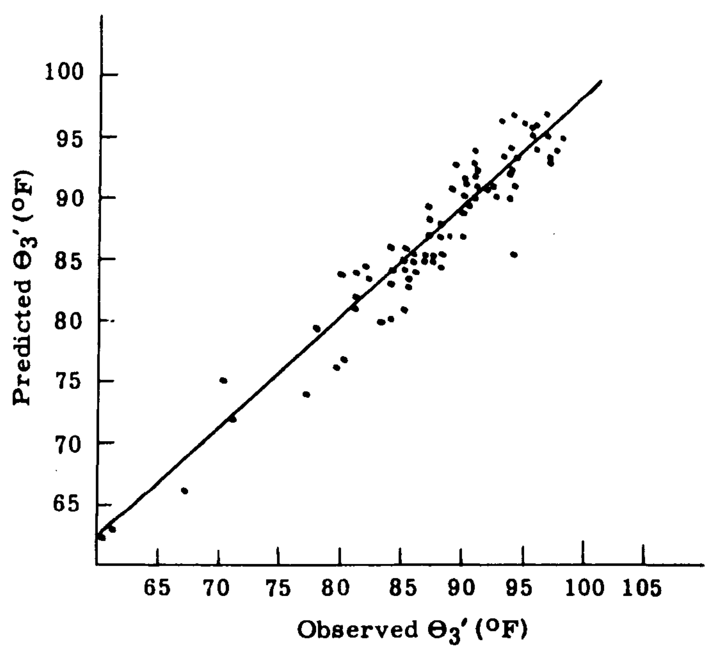

Figure 15. The relationship between the observed and the predicted Θ_3' for summer using T_2, S, W, and M_3' as predictors.

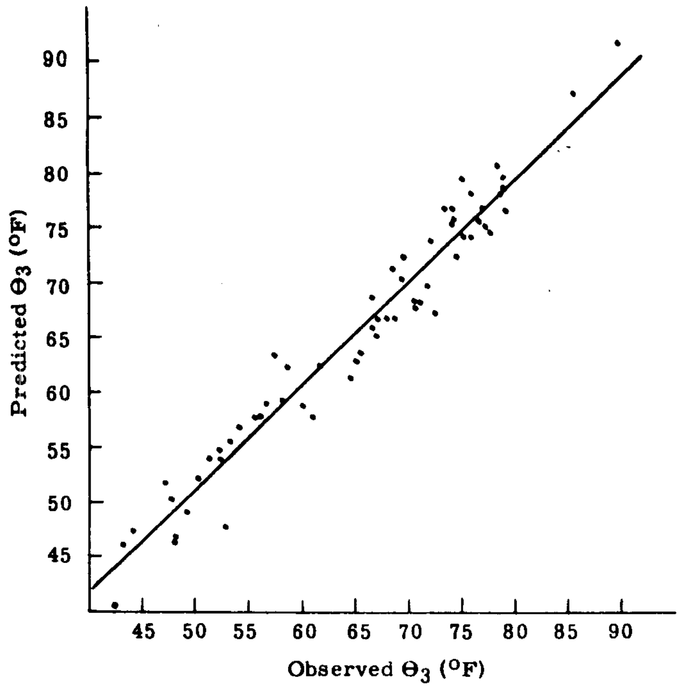

Figure 16. The relationship between the observed and the predicted Θ_3 for fall using T_u, T_1, S, C, and M_3 as predictors.

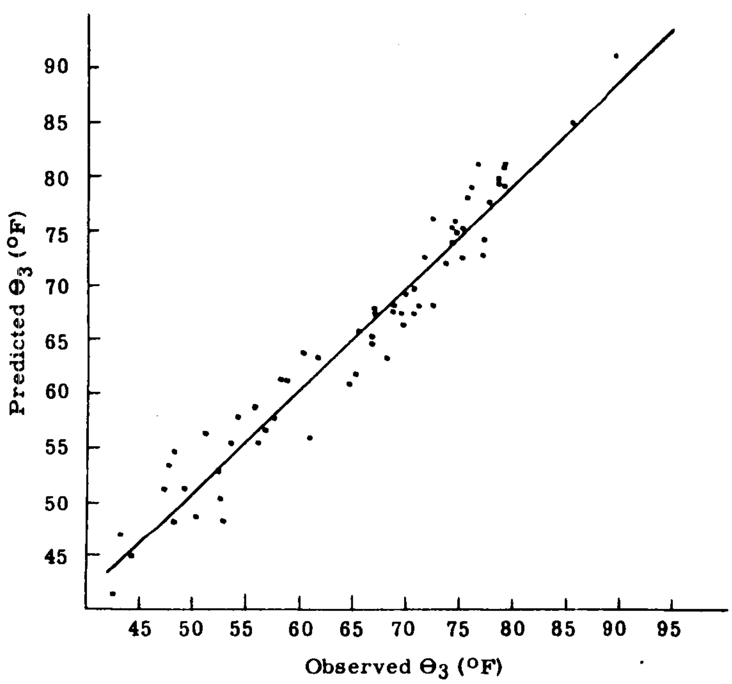

Figure 17. The relationship between the observed and the predicted Θ_3 for fall using T_2, S, C, and M_3 as predictors.

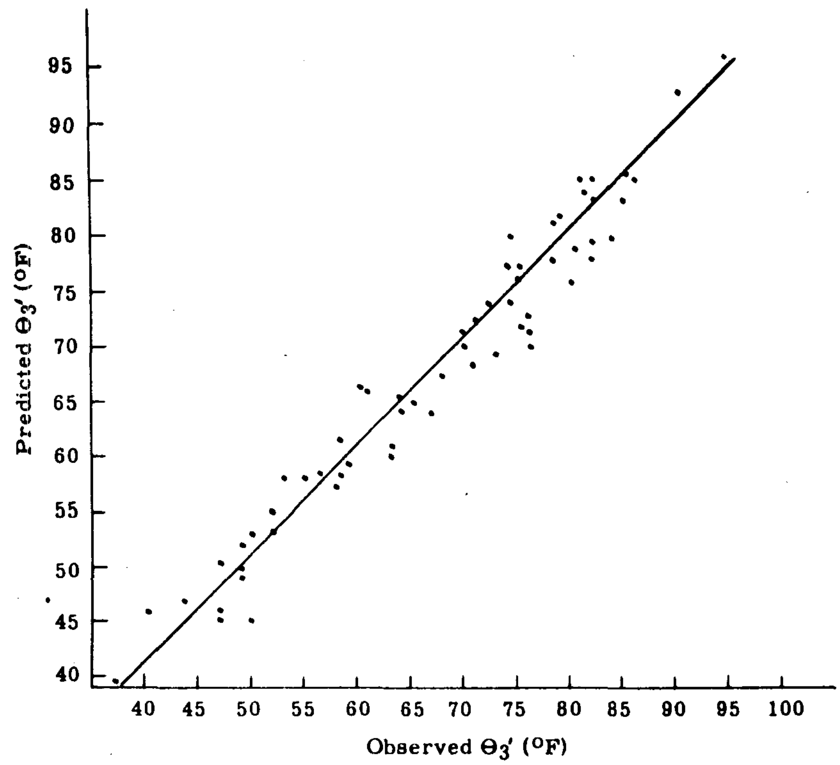

Figure 18. The relationship between the observed and the predicted Θ_3' for fall using T_u, T_1, S, and M_3' as predictors.

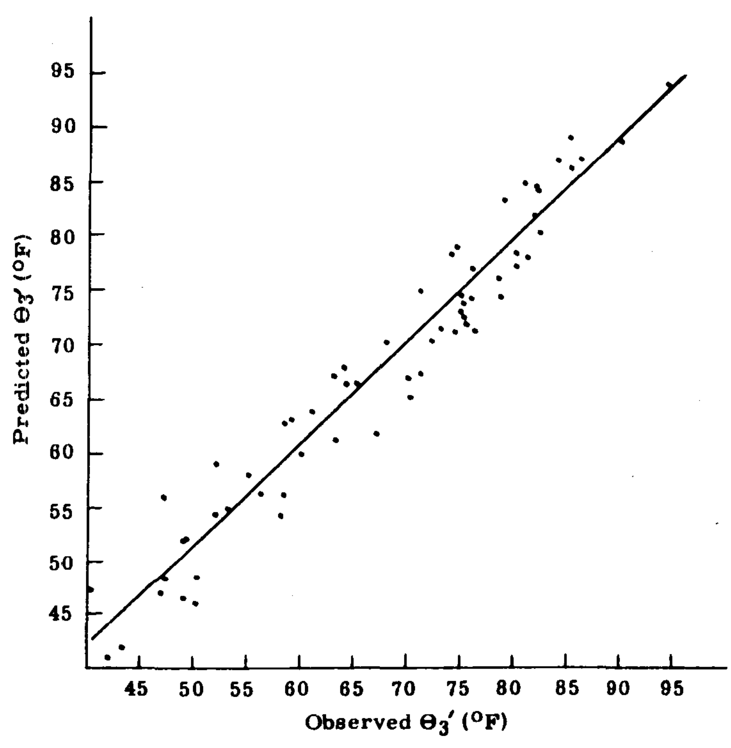

Figure 19. The relationship between the observed and the predicted Θ_3' for fall using T_2, S, and M_3' as predictors.

Examination of the data presented in Figures 8 through 19 shows that straight lines fit the plotted points. There are no changes in slope in the lines as was the case for the winter data. Changes in slope were not expected since above freezing temperatures were not encountered.

The amount of scatter in the plotted points indicates the amount of variation not explained by the regression line. Examination of Figures 8 through 19 indicates that for the fall season there is the smallest amount of variation not explained by the regression analysis. For all seasons the amount of scatter is less for the analysis employing T_u and T_1 than when T_2 was employed.

2. The soil temperature for deeper levels

The observed and the predicted soil temperatures have been compared for each cover and season at the remaining depths. These comparisons were made to determine whether any points diverted greatly from the predicted values and to discover changes in the slopes of the resulting regression line. A careful review of these diagrams shows that no such irregularities exist, and that the multiple correlation coefficients are adequate estimates of the variability not explained by the regression analysis.

The multiple correlation coefficients for the depths below three inches are higher than the corresponding coefficients for the three inch depth. The multiple correlation coefficients were obtained for the six inch depth, were the largest, and 24 inch depth produced coefficients which were larger than those for the twelve inch depth.

VI. CONCLUSIONS

A. The Prediction of the Three Inch Soil Temperature

1. The temperatures of the invading air mass T_u were found to contribute significantly to the three inch soil temperatures. The magnitudes of the partial regression coefficients associated with this variable varied with season and cover, but signs of all these coefficients were positive. These partial regression coefficients ranged in size from 0.1 to 0.2. If other factors remained constant, the invasion of an air mass 10° F. cooler than the present air mass reduced the soil temperatures by 1° or 2° F.
2. The previous air temperature T_1 was successfully employed as a predictor in conjunction with the temperature of the invading air. The previous air temperature contributed more to the soil temperatures than the temperature of the invading air, and partial regression coefficients associated with the previous air temperature varied from 0.3 to 0.5.
3. As a substitute analysis, the current air temperature T_2 was used in place of T_u and T_1. The partial regression coefficients obtained by use of this variable ranged from about 0.4 to 0.7. These coefficients were larger than

those for either of the two preceding variables. For every degree change in the current air temperature there was a corresponding charge of 0.3° to 0.7° F. in the three inch soil temperature.

4. Changes in the daily total solar energy resulted in proportional changes in soil temperatures. If other factors remained constant a change of 100 calories in amount of solar energy received each day resulted in a change of from 1° to 2.5° F. in the three inch soil temperature.
5. There is a marked tendency for higher afternoon soil temperatures to be associated with cloudy nights, but during the cooler portion of the year the amount of night cloudiness did not contribute significantly to the analysis. During the remainder of the year an overcast night sky increased the soil temperatures by 2° to 4° F., when other factors remained constant.
6. The effect of wind was also most marked during the warm seasons of the year. During these periods an increase in the wind velocity aided in the transport of heat from the surface, and thus decreased the soil temperatures. During the cooler portion of the year wind did not have as marked an influence, and the effect appeared to be in the opposite direction. For a cold soil surface higher wind speeds were associated with soil warming.
7. Soil moisture exerted a pronounced effect on the tem-

perature of the soil during the warmer seasons of the year. Its effect was most felt during these seasons because of the more pronounced day to day variations in the moisture content of the soil. According to these analyses, higher moisture content in the soil resulted in lower soil temperatures. The magnitudes of the partial regression coefficients depended on the moisture level in the soil.

8. There was a large seasonal difference in the precision with which the soil temperatures were estimated. The winter season provided the poorest estimate of the three inch soil temperatures since only about 70 per cent of the variation was explained by the regression analysis. The analysis for fall provided the best estimates by explaining about 95 per cent of the variation in the three inch soil temperatures.

9. When the analyses which employed T_u and T_l are compared with those which employed T_2, it is apparent that the first explained a higher per cent of the variation in the three inch soil temperatures. The amount of variation explained by T_u and T_l was only greater than the amount explained by T_2 only by a small amount, so it is doubtful that the sytem using two variables should be employed.

B. Prediction of Soil Temperatures at Deeper Levels

1. The use of the soil temperature observed at the next shallower level as an independent variable provides an excellent prediction for the temperature of the soil. In some cases this is the only variable which explains a significant amount of the variation in the soil temperatures.
2. The antecedent temperature provided a small and negative effect upon the soil temperature when other factors remained constant. The small magnitude and negative signs of the resulting partial correlation coefficients were due to high relationship between the antecedent temperature and the soil temperature at the next shallower level.
3. Soil moisture exhibited an erratic effect upon the soil temperatures at these deeper levels. Its variation was not consistent between seasons or for the different covers, since it varied in both magnitude and sign. The magnitude of the significant partial regression coefficients depended upon the level of moisture.
4. The multiple correlation coefficients were higher for the deeper levels than at the three inch depth. The highest coefficients were obtained for the six inch depth, with

the twenty-four inch depth displaying higher regression coefficients than the twelve inch depth.

VII. SUMMARY

Soil temperatures have an important effect on agriculture. They exert a control on the rate of germination and growth, on the activity of the soil's microbiological population, and on the weathering processes of the soil. Since soil temperatures are difficult to measure, there is a deficiency of soil temperature records. This work was instigated to provide a method for estimating soil temperatures from meteorological and soil factors.

Soil temperature observations were taken at three, six, twelve, and twenty-four inches below the surface with thermocouples. The measurements consisted of two daily temperature observations which were taken at each depth in each of three fallow and three grass plots. The dependent variables for the prediction analysis were the averages of the six daily observations.

Two models were used to obtain regression equations for prediction of the three inch soil temperature. In the first model, the air temperatures used as predictors were the temperature of the invading air T_u, defined as the upstream air temperature, and the temperature of the air twenty-four hours previous to the soil temperature observation T_1. The second model utilized the temperature of the air at the time of the soil temperature observation. In both regression analyses the daily solar energy S, the average night cloudiness C, the average wind velocity W, and the average soil moisture resistance M_3 were used. The latter measurements were obtained from Bouyoucos soil moisture blocks.

For deeper soil levels the antecedent air temperatures were used as predictors. These antecedent temperatures were: for the six inch depth, T_3 the air temperature three hours earlier than the observation time; for the twelve inch depth, T_4 the air temperature ten hours earlier; and for the twenty-four inch depth, T_5 the air temperature thirty-two hours earlier. The observed soil temperature at the next shallower depth and the average soil moisture resistance were also used as independent variables.

The air temperatures expressed as T_u, T_1, and T_2 were positively correlated with the three inch soil temperatures. From the three inch soil temperature analysis, which employed T_u and T_1 as predictors, it was noted that T_1 exhibited a greater effect on the soil temperature than T_u. When other factors were held constant a change of 1° F. in T_1 changed the three inch soil temperature by 0.3° to 0.7° F., while a change of 1° F. in T_u only yielded a 0.1° to 0.2° F. soil temperature change. From the analysis based on the second model, which used T_u and T_1 along with the other variables as predictors, explained a larger per cent of variability than the second model; but the increase in precision was so small that it does not appear worthwhile to employ the two variable model.

The daily total of calories of solar energy received was found to be positively correlated with the three inch soil temperature. When S was combined with the other independent variables, its effect did not vary a great deal. Each 100 calorie change in the daily solar energy was associated with a 1° to 2.5° F. change in the three inch soil temperature.

Clouds occurring at night reduced the amount of energy lost by nocturnal radiation and increased the observed soil temperature. This effect was most pronounced during the warmer part of the year. An overcast night sky increased the three inch soil temperature the following afternoon by 2° F. over the temperature which would have followed a clear night.

The average wind speed was negatively correlated with the three inch soil temperature during the warm portion of the year. Wind provides a mechanism for the mixing of the lower atmosphere and for heat removal from the surface. Average wind velocities of ten miles per hour reduced the three inch temperature by as much as 4° or 5° F. over a near calm condition.

According to these results the three inch soil moisture was not correlated with the three inch soil temperature during the winter and spring seasons. The failure in obtaining a significant relationship was due to the small variation in soil moisture during the cool seasons of the year. In summer and fall, when the variability was greater, lower soil moisture values were associated with higher soil temperatures. This negative relationship was due to the decrease in specific heat as the soil became drier.

For deeper soil levels the temperature of the next shallower depth was employed as a variable. The three inch soil temperature was used to predict the six inch soil temperature, the six inch soil temperature was used to predict that at twelve inches, while the twelve inch temperature was used as a predictor for the twenty-four inch depth. The temperatures at these shallower depths provided the best predictors for the soil temperatures at levels below three inches.

The simple correlation coefficients between the antecedent air temperatures and soil temperatures for depths below three inches were positive; but when expressed in terms of the partial regression coefficients, these relationships became negative. These negative values seem to indicate that a decreasing air temperature is associated with an increasing soil temperature. This paradox is the result of the closer relationship between antecedent air temperature and the soil temperature at the shallower depth than on the temperature at the depth under investigation.

For the levels below the three inch depth, soil moisture exhibited an erratic effect. It was usually positively correlated with the soil temperature of the same depth, but sometimes the correlation was negative. No physical explanation for this variation was found.

In each case the independent variables were combined into a prediction equation according to a multiple regression analysis. For the three inch soil temperatures the prediction equation explained from 70 to 95 per cent of the variation in the soil temperature, leaving 30 to 5 per cent unexplained. The greatest per cent of explained variation occurred in the fall, while the smallest percentage was associated with the winter season. The large amount of unexplained variation, 30 per cent for the winter season, resulted from the difference in the response of frozen and unfrozen soil with the same weather conditions. A separate analysis should be conducted for days with frozen soil.

The equations used to predict the temperatures below the three inch depth explained from 85 to 99 per cent of the variation in the soil temperatures. On many occasions more than 95 per cent of the variation was explained, and in only a few cases did the amount of explained variation fall below 90 per cent.

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X. APPENDICES

APPENDIX A

Table 45. Average of six daily soil temperature observations taken at all depths and under each cover

Date	Grass				Fallow			
	Depth in inches				Depth in inches			
	3	6	12	24	3	6	12	24
6/12/53	88.2	82.2	74.6	69.1	96.2	87.2	78.2	71.2
6/15/53	82.7	78.1	73.9	69.7	87.8	82.4	77.6	72.4
6/16/53	85.2	80.7	74.7	69.9	90.8	84.8	78.8	72.7
6/17/53	87.6	81.7	74.6	70.0	94.0	86.3	78.6	73.0
6/18/53	90.2	83.9	76.1	70.3	97.2	89.0	80.3	73.5
6/19/53	90.6	84.6	76.7	70.4	97.2	89.6	81.0	73.5
6/20/53	89.4	84.4	77.7	72.0	94.8	88.9	82.0	74.9
6/21/53	88.9	83.6	76.8	71.8	93.8	87.6	80.6	74.8
6/22/53	89.4	83.4	76.4	71.8	94.7	87.4	80.3	75.2
6/23/53	91.0	84.6	77.2	72.2	96.0	88.3	80.7	75.4
6/24/53	90.9	84.6	77.4	72.2	95.8	88.6	81.3	75.4
6/25/53	86.0	82.0	77.5	73.2	87.7	85.0	80.6	76.1
6/26/53	83.9	80.4	75.8	72.3	82.3	80.2	77.2	74.6
6/27/53	86.8	81.9	75.1	71.0	91.4	86.1	76.8	74.0
6/28/53	83.0	79.4	75.8	72.0	81.8	79.8	75.0	72.0
6/29/53	90.1	85.0	77.3	72.0	95.9	87.4	78.4	73.3
6/30/53	90.9	86.4	79.4	73.1	96.6	90.0	81.7	75.2
7/ 1/53	85.3	81.6	77.2	72.9	89.4	84.4	80.4	75.6
7/ 2/53	87.0	83.0	77.5	73.3	91.3	85.8	80.0	75.6
7/ 3/53	89.4	83.8	77.4	73.1	93.8	86.4	80.0	75.4
7/ 4/53	84.6	79.8	75.2	72.7	85.6	82.2	78.8	75.6
7/ 6/53	81.2	80.0	77.6	73.2	80.4	79.5	77.9	75.2
7/ 7/53	84.5	81.2	76.8	73.6	85.9	80.4	75.6	73.9
7/ 8/53	81.7	80.6	77.4	74.0	83.8	80.8	76.5	74.2
7/ 9/53	81.0	79.0	75.5	73.1	86.1	80.8	75.5	73.8
7/10/53	81.0	78.5	74.6	72.6	87.8	81.4	75.3	73.4
7/11/53	79.8	77.6	74.2	72.0	87.0	81.0	75.4	73.0
7/13/53	81.6	79.0	75.0	72.2	89.0	83.0	76.6	73.3
7/14/53	82.6	79.6	75.2	72.2	90.9	84.6	77.5	73.4
7/15/53	82.3	79.2	75.2	72.2	90.5	84.2	77.6	73.7

	3	6	12	24	3	6	12	24
7/16/53	81.0	78.6	75.3	72.4	87.3	82.8	77.6	74.2
7/17/53	83.6	80.4	75.6	72.2	90.2	83.2	76.6	73.8
7/18/53	86.1	81.4	75.9	72.2	95.4	86.5	78.2	73.6
7/21/53	83.7	80.8	76.8	73.1	85.1	82.0	79.0	75.4
7/22/53	83.8	82.2	77.2	73.4	84.2	81.6	77.8	75.1
7/23/53	83.4	80.9	76.4	73.8	89.6	81.8	76.2	74.7
7/24/53	84.0	81.0	75.6	72.5	94.0	85.4	76.9	74.0
7/25/53	84.6	81.4	76.4	72.8	94.4	86.5	78.9	74.6
7/27/53	86.6	84.0	78.2	74.0	94.3	89.7	81.8	75.8
7/28/53	89.8	84.3	78.2	73.6	98.5	90.4	81.8	76.0
7/29/53	90.0	84.4	78.8	74.5	98.0	90.0	82.8	77.0
7/30/53	90.0	84.1	79.0	74.6	97.8	90.0	83.0	78.0
8/ 1/53	93.4	88.0	81.4	76.3	101.2	93.4	85.3	79.2
8/ 3/53	91.0	86.2	80.8	76.1	97.4	91.4	84.7	79.2
8/ 4/53	82.4	81.2	79.0	76.6	83.6	83.2	81.9	79.4
8/ 5/53	84.3	81.4	77.8	75.4	85.6	82.2	78.7	77.4
8/ 6/53	82.4	80.4	77.6	75.4	82.6	80.3	77.4	76.2
8/ 7/53	81.0	79.8	77.6	75.3	81.2	79.8	77.4	76.2
8/ 9/53	81.1	78.5	74.9	74.2	86.2	79.9	74.3	74.5
8/10/53	80.4	78.7	75.0	73.8	87.7	81.4	75.1	73.8
8/11/53	80.6	77.6	75.1	74.0	88.8	81.4	75.8	74.4
8/12/53	80.6	79.0	76.0	74.3	86.2	80.3	76.6	74.2
8/13/53	81.6	79.0	75.6	73.8	87.9	81.8	77.0	74.8
8/15/53	79.0	77.3	75.5	73.6	85.2	81.2	77.6	74.6
8/16/53	74.4	74.4	74.3	73.7	77.2	77.0	76.5	75.1
8/17/53	76.1	75.1	73.9	73.2	81.7	78.3	75.5	74.8
8/18/53	77.1	75.4	73.2	72.4	84.2	79.2	74.8	73.5
8/19/53	78.1	75.8	73.2	72.6	85.3	80.2	75.1	73.7
8/20/53	78.2	76.0	73.4	72.4	85.0	80.4	75.6	73.9
8/21/53	77.8	75.5	73.0	72.1	84.2	79.4	75.3	73.8
8/22/53	80.2	76.6	73.3	72.0	87.4	80.8	75.4	73.6
8/24/53	82.4	78.8	74.7	72.4	89.2	83.3	78.0	74.3
8/25/53	83.6	79.4	75.2	72.8	90.6	83.8	77.7	74.0
8/26/53	84.0	80.2	75.6	73.2	91.0	84.8	78.9	75.1
8/27/53	84.7	80.5	76.0	73.2	91.1	85.0	79.2	75.4
8/29/53	85.3	81.0	76.6	73.6	91.2	85.0	79.4	75.8
8/30/53	85.7	81.0	76.7	73.8	90.6	84.5	79.6	76.0
8/31/53	89.2	83.8	77.8	74.4	94.6	87.6	80.7	76.1
9/ 1/53	89.6	84.7	79.0	74.8	94.8	88.4	82.0	77.1
9/ 2/53	85.5	82.2	77.9	74.9	90.4	85.0	81.4	77.4

	3	6	12	24	3	6	12	24
9/ 4/53	72.0	72.0	72.0	73.6	71.3	73.6	73.5	74.9
9/ 5/53	74.5	73.1	71.2	72.4	74.4	72.4	71.0	73.6
9/ 7/53	75.4	73.5	71.2	71.8	75.0	72.3	70.2	71.6
9/ 8/53	74.4	72.5	70.1	70.8	74.9	71.3	68.8	70.4
9/ 9/53	76.0	73.2	70.6	70.8	79.2	73.4	69.7	70.3
9/10/53	78.5	74.0	70.0	69.2	81.0	75.7	70.8	69.8
9/11/53	79.3	76.6	72.2	70.2	86.2	80.0	73.4	71.4
9/12/53	73.8	73.2	71.8	71.5	78.8	75.4	72.8	71.6
9/14/53	74.2	72.3	70.1	70.0	80.6	75.6	70.9	70.2
9/15/53	75.8	73.4	70.1	69.8	82.5	76.6	71.0	70.4
9/16/53	75.2	73.2	70.0	69.2	82.5	76.8	71.6	70.5
9/17/53	76.8	74.0	71.0	69.9	84.3	78.3	73.0	70.8
9/19/53	77.4	75.2	71.6	70.3	78.8	75.6	72.8	71.5
9/21/53	69.5	69.7	69.6	70.5	72.8	71.2	70.1	71.2
9/22/53	72.4	69.5	67.2	69.3	76.5	70.6	67.4	69.6
9/23/53	71.6	69.2	66.7	68.3	76.2	70.4	67.3	69.0
9/24/53	71.4	69.2	67.1	68.0	75.5	71.0	68.4	68.8
9/25/53	74.6	71.2	67.6	67.8	80.2	73.9	69.0	68.2
9/28/53	79.3	73.9	69.2	68.0	85.1	77.1	70.7	69.0
9/29/53	79.0	74.7	70.3	68.3	85.4	78.8	72.6	69.6
9/30/53	77.0	74.0	70.4	69.3	81.6	77.2	73.0	70.8
10/ 1/53	77.9	73.1	69.4	69.2	82.0	75.6	71.1	70.9
10/ 2/53	78.6	74.4	70.4	69.0	82.8	77.2	72.4	70.4
10/ 5/53	67.2	67.0	66.4	68.8	65.6	66.2	66.4	69.4
10/ 6/53	61.0	62.2	64.0	67.8	58.6	61.0	63.6	68.2
10/ 7/53	64.6	63.2	62.9	66.4	63.8	61.7	61.2	66.0
10/ 8/53	65.5	63.6	62.2	65.4	64.2	61.8	60.5	64.4
10/ 9/53	67.4	65.2	62.9	65.2	68.2	64.0	61.2	63.8
10/12/53	66.6	65.2	63.6	65.0	70.0	66.2	63.5	64.6
10/13/53	66.9	65.2	63.4	64.7	71.2	66.6	63.4	64.4
10/14/53	68.6	66.0	63.6	64.6	73.0	67.2	63.3	64.4
10/15/53	70.6	67.2	63.7	64.4	76.0	68.8	64.2	64.4
10/16/53	68.8	66.6	63.8	64.1	75.0	69.0	64.5	64.6
10/18/53	69.9	67.3	64.6	64.6	75.6	70.0	65.6	65.0
10/19/53	69.6	67.5	65.2	65.0	74.8	70.2	66.4	65.8
10/21/53	70.6	67.6	65.2	65.0	75.6	70.6	66.4	66.0
10/22/53	68.1	66.4	65.1	65.0	70.4	67.6	66.1	65.8
10/23/53	65.2	64.9	64.4	65.2	67.0	66.2	65.2	66.4
10/27/53	52.6	55.2	59.2	63.4	50.2	54.2	58.6	63.4
10/28/53	54.4	55.4	57.0	62.0	52.3	53.9	55.8	61.8

	3	6	12	24	3	6	12	24
10/29/53	56.8	55.6	55.4	60.7	56.8	54.5	54.0	60.2
10/30/53	58.4	56.8	55.4	60.0	59.2	55.6	54.0	59.0
11/ 2/53	60.2	58.1	56.2	59.1	63.2	58.4	55.6	58.4
11/ 3/53	57.5	57.6	57.4	60.0	60.3	58.6	57.1	59.3
11/ 4/53	56.1	56.8	57.0	60.0	58.4	57.7	57.0	59.3
11/ 5/53	50.4	52.1	53.7	59.0	50.4	52.2	54.1	59.0
11/ 6/53	48.4	50.0	52.2	58.6	47.0	48.4	51.0	59.4
11/ 9/53	49.2	49.0	49.7	55.6	49.0	47.5	48.3	54.6
11/10/53	51.2	50.0	49.4	55.0	52.1	49.0	48.4	53.8
11/11/53	52.3	51.6	50.8	55.0	53.4	50.8	49.8	53.8
11/12/53	53.4	51.9	50.8	54.8	55.0	51.6	49.9	53.9
11/13/53	55.7	53.6	51.8	54.8	58.5	54.0	51.1	53.8
11/17/53	58.8	56.1	54.0	55.8	61.4	56.9	54.0	55.4
11/18/53	61.6	58.5	55.4	56.0	64.3	59.6	55.8	55.5
11/20/53	52.4	54.3	56.6	57.1	49.0	54.2	56.6	57.5
11/23/53	48.2	48.2	49.6	54.6	47.6	47.0	48.6	53.9
11/24/53	47.3	49.2	51.7	54.8	47.3	48.6	49.8	53.8
11/25/53	42.4	45.0	49.1	55.2	42.0	45.0	47.8	54.7
11/27/53	44.3	46.0	47.8	53.4	43.7	45.0	47.2	52.8
11/28/53	43.1	43.2	45.9	52.3	40.6	41.4	45.6	51.4
11/30/53	47.8	47.4	47.2	51.1	49.2	47.5	46.7	50.4
12/ 1/53	48.0	46.4	46.4	50.8	50.0	46.6	45.6	49.8
12/ 3/53	54.5	53.2	50.9	51.4	55.2	53.2	50.5	50.9
12/ 4/53	45.8	47.4	49.6	52.7	44.6	46.3	49.2	52.2
12/ 7/53	46.5	45.8	46.1	51.0	46.0	44.8	45.0	49.8
12/ 8/53	48.4	47.2	46.8	50.2	49.4	47.0	46.0	49.7
12/10/53	43.0	42.6	44.4	50.0	42.8	41.4	43.8	49.2
12/11/53	41.8	42.3	44.3	49.5	41.0	41.2	43.4	48.6
12/15/53	37.2	38.4	41.5	48.5	33.8	37.0	41.5	47.4
12/16/53	34.6	37.2	41.5	48.4	34.2	37.2	41.4	47.3
12/17/53	33.2	35.4	39.8	47.4	32.6	35.2	39.8	46.2
12/18/53	32.5	33.5	38.1	45.4	32.1	33.0	37.8	44.6
12/21/53	46.0	45.1	43.7	45.1	47.0	44.8	42.8	43.8
12/23/53	33.6	36.2	40.8	47.0	31.4	34.8	40.0	45.6
12/24/53	34.6	36.2	39.4	45.4	33.1	34.4	38.2	44.3
12/28/53	39.6	39.8	40.4	44.6	34.2	35.0	38.2	43.0
12/29/53	38.2	38.2	39.4	43.9	33.5	34.9	37.6	42.4
12/30/53	37.9	38.9	40.2	44.4	33.8	35.6	38.2	42.6
12/31/53	38.6	37.3	38.5	43.6	34.0	34.7	37.7	42.2
1/ 1/54	43.0	41.0	39.8	43.2	43.6	39.6	37.9	41.6

	3	6	12	24	3	6	12	24
1/ 2/54	44.6	43.2	41.8	44.4	46.5	43.5	41.5	43.4
1/ 4/54	40.6	40.0	40.8	44.8	38.8	38.4	40.4	44.2
1/ 5/54	40.8	39.7	40.2	44.4	38.8	37.6	39.6	43.5
1/ 6/54	41.0	40.8	41.0	44.8	39.6	39.0	40.2	43.8
1/ 7/54	43.0	41.2	40.0	43.7	42.1	39.2	39.0	42.8
1/ 8/54	46.8	43.8	41.6	43.4	49.3	43.8	40.8	42.6
1/ 9/54	40.5	42.4	43.5	45.8	39.8	41.6	43.0	45.2
1/11/54	33.2	35.3	38.8	44.7	33.3	35.3	39.4	44.4
1/13/54	32.0	33.6	36.6	42.9	31.9	33.0	36.5	42.3
1/14/54	33.1	33.8	36.4	42.0	33.0	33.2	36.2	41.5
1/15/54	34.1	34.8	37.0	42.0	33.4	33.4	35.8	41.0
1/17/54	33.2	34.5	37.4	42.6	32.4	33.6	36.8	41.6
1/18/54	33.2	33.8	36.4	41.7	32.8	33.0	35.7	40.3
1/19/54	41.4	37.9	36.6	40.4	36.6	32.3	34.8	39.3
1/21/54	34.8	36.0	40.3	44.5	30.6	35.6	38.2	41.6
1/22/54	33.8	34.7	37.8	42.8	33.1	33.8	37.0	41.4
1/23/54	32.8	33.3	36.1	41.2	32.0	32.2	35.0	39.8
1/25/54	34.4	33.8	36.1	40.5	35.4	32.8	35.0	38.6
1/27/54	34.4	35.6	38.1	42.4	32.8	34.6	37.2	40.8
1/28/54	32.1	33.4	35.7	40.7	31.7	32.6	35.2	39.6
1/29/54	33.2	33.6	36.0	40.5	32.5	32.8	35.1	39.3
1/30/54	33.4	34.2	36.2	40.0	33.2	33.6	35.8	40.0
2/ 1/54	35.8	35.7	36.5	40.0	35.6	33.8	35.8	39.4
2/ 2/54	43.6	39.8	37.4	40.0	43.5	38.0	36.2	39.2
2/ 3/54	44.3	42.4	40.5	41.6	45.1	41.8	39.0	40.1
2/ 4/54	44.7	42.3	39.8	41.6	46.4	41.8	39.2	40.8
2/ 5/54	44.8	42.5	41.0	42.3	45.7	42.2	40.0	41.6
2/ 7/54	41.0	40.0	39.7	42.8	38.3	37.6	39.3	42.2
2/ 8/54	43.8	40.1	39.1	41.7	45.0	39.3	38.0	41.0
2/ 9/54	49.1	44.2	40.4	41.8	53.2	45.2	40.0	40.7
2/10/54	47.8	44.5	42.0	43.0	51.2	45.8	41.8	42.0
2/11/54	41.6	41.2	41.3	43.2	42.6	41.4	41.2	42.9
2/12/54	36.6	38.4	39.6	43.4	35.3	36.8	40.0	43.4
2/15/54	54.7	51.8	47.2	44.0	59.0	54.0	49.8	44.0
2/16/54	49.8	49.0	47.8	46.0	50.2	49.4	47.9	46.2
2/17/54	49.6	46.6	44.8	45.6	51.0	47.0	44.8	45.6
2/18/54	50.4	47.0	44.8	45.6	51.0	47.4	44.2	45.5
2/22/54	48.5	45.2	43.2	45.0	49.2	45.1	43.0	44.8
2/23/54	42.4	43.1	44.2	45.6	41.3	42.7	43.9	45.3
2/24/54	48.6	44.7	42.2	44.4	50.8	44.8	41.8	44.2

	3	6	12	24	3	6	12	24
2/26/54	48.2	45.2	43.6	45.4	50.0	45.1	43.2	45.0
3/ 1/54	45.4	42.7	41.2	44.5	45.0	41.9	41.2	44.2
3/ 4/54	34.6	36.6	39.4	43.9	33.4	35.4	39.2	43.3
3/ 5/54	35.2	36.1	38.0	42.6	33.1	34.8	38.0	42.3
3/ 7/54	49.6	43.9	39.2	41.2	50.7	41.8	37.4	40.0
3/ 8/54	49.6	45.6	41.2	41.2	53.4	45.7	39.8	40.0
3/ 9/54	50.0	46.2	43.4	43.4	52.9	46.2	42.4	42.0
3/11/54	48.4	46.0	44.2	44.5	51.0	47.4	44.4	44.4
3/12/54	53.6	49.4	45.4	44.1	59.8	51.7	46.0	44.3
3/15/54	43.9	41.8	41.0	44.4	46.2	41.8	41.0	44.8
3/16/54	48.8	44.8	41.8	44.2	52.1	45.5	41.5	43.9
3/17/54	49.7	46.2	43.4	44.3	55.4	48.3	43.7	44.0
3/19/54	48.0	46.2	45.2	45.6	48.8	46.6	45.8	45.8
3/22/54	50.1	46.8	44.5	45.4	51.4	46.6	44.1	45.2
3/24/54	54.4	49.6	45.8	45.2	57.3	50.0	45.4	44.9
3/25/54	55.7	54.2	50.8	47.2	56.0	54.2	50.4	46.9
3/26/54	57.0	52.5	48.2	47.5	57.2	51.4	47.0	46.6
3/27/54	58.4	53.6	49.0	47.6	61.3	53.7	47.8	47.0
3/28/54	59.6	55.1	50.4	48.3	64.2	56.6	49.8	47.8
3/29/54	42.9	46.4	49.2	50.0	38.8	43.8	48.0	49.6
3/30/54	42.6	43.9	45.2	48.6	40.0	41.2	43.9	47.8
3/31/54	49.0	46.5	44.5	46.9	51.5	46.7	43.6	46.4
4/ 1/54	51.7	47.6	44.2	46.2	55.7	48.0	43.4	45.5
4/ 2/54	56.3	50.9	46.2	45.9	64.2	54.6	46.2	45.3
4/ 5/54	61.9	56.2	49.6	46.9	69.5	60.3	50.3	46.9
4/ 6/54	70.5	63.6	55.0	49.1	75.7	65.8	55.6	49.3
4/ 7/54	65.2	62.4	57.4	51.2	71.2	65.1	58.0	51.7
4/ 8/54	62.5	59.6	55.8	52.8	67.5	61.4	55.9	52.9
4/ 9/54	61.7	56.8	53.2	51.4	69.0	59.8	53.6	52.0
4/10/54	64.8	59.8	54.8	51.6	72.8	63.9	55.8	51.4
4/12/54	63.8	60.6	55.8	53.4	64.8	59.9	55.2	53.7
4/13/54	65.5	61.2	56.3	53.6	69.1	62.2	55.4	53.4
4/15/54	63.8	63.0	60.0	55.6	64.2	62.7	59.2	55.4
4/17/54	63.4	58.7	53.8	52.8	68.1	59.1	53.7	53.1
4/20/54	66.4	63.0	58.2	55.0	72.9	65.0	59.2	55.4
4/22/54	58.1	58.2	58.4	57.2	57.2	58.2	58.8	57.6
4/23/54	65.8	61.4	57.4	56.0	67.1	60.8	57.1	56.5
4/26/54	73.2	68.6	63.8	59.0	73.0	67.7	62.6	58.4
4/27/54	65.6	64.8	63.4	59.7	64.4	63.6	62.2	59.6
4/28/54	64.8	63.1	61.8	59.9	64.0	61.7	60.4	59.4

	3	6	12	24	3	6	12	24
4/29/54	70.2	65.7	61.4	59.3	70.4	64.2	59.7	58.8
5/ 3/54	57.1	58.8	60.2	60.6	53.8	56.8	59.2	60.6
5/ 4/54	61.9	59.7	57.7	59.4	59.8	56.6	55.2	58.4
5/ 5/54	64.1	61.3	58.2	58.1	63.0	59.0	56.0	57.2
5/ 6/54	60.6	58.8	57.8	57.8	59.9	56.6	55.6	56.6
5/ 7/54	62.0	60.0	58.0	57.8	60.6	59.4	56.0	56.8
5/10/54	63.4	59.5	55.9	56.2	64.2	58.4	54.1	55.0
5/11/54	66.0	62.5	58.6	57.5	66.1	61.4	56.8	56.4
5/12/54	66.6	62.8	58.6	57.0	67.0	61.4	56.6	55.9
5/13/54	68.6	64.4	59.6	57.4	69.6	63.0	57.5	56.2
5/14/54	70.6	65.8	60.7	58.4	73.6	64.8	58.6	57.0
5/17/54	70.7	68.1	63.4	59.6	71.0	67.3	62.4	59.2
5/18/54	72.1	68.6	63.9	60.7	76.6	68.8	62.4	59.9
5/19/54	67.0	65.8	63.6	61.1	68.6	65.0	62.5	60.6
5/20/54	69.8	65.9	61.8	60.4	75.6	66.6	60.8	60.0
5/21/54	70.0	66.1	62.1	60.4	76.7	68.4	61.4	59.8
5/24/54	74.8	70.6	65.2	61.1	74.7	69.2	64.0	60.6
5/25/54	68.8	67.0	65.1	62.2	67.0	65.2	63.9	62.0
5/26/54	68.3	66.0	63.9	62.0	68.2	64.4	62.4	61.4
5/27/54	75.3	70.4	65.0	62.0	75.8	69.6	64.0	61.2
5/28/54	69.4	68.7	66.6	63.0	68.2	67.5	65.4	62.6
5/31/54	73.2	69.6	65.6	62.6	63.6	68.8	64.6	61.6
6/ 1/54	67.7	66.2	65.3	63.4	67.4	65.6	64.6	63.2
6/ 2/54	62.6	62.3	63.0	63.2	61.8	61.0	61.9	62.6
6/ 3/54	60.5	61.0	61.8	62.6	59.6	59.6	60.7	62.0
6/ 4/54	69.8	65.1	61.4	61.2	70.9	64.6	60.9	61.4
6/ 7/54	76.6	72.1	66.6	62.4	78.2	72.0	66.0	62.2
6/ 8/54	78.2	72.8	67.4	63.1	80.0	72.4	66.8	62.8
6/ 9/54	70.8	68.8	67.7	64.2	71.6	68.2	67.0	64.3
6/10/54	79.6	73.8	67.6	64.0	81.4	73.8	67.2	64.0
6/11/54	82.5	77.0	70.6	65.4	84.0	76.6	70.0	65.2
6/14/54	84.2	80.0	74.1	68.0	84.8	79.4	73.0	68.0
6/15/54	79.8	76.8	73.5	68.4	79.6	75.6	72.3	67.9
6/16/54	83.5	78.4	73.0	68.5	84.8	77.6	71.8	68.0
6/17/54	84.2	80.3	74.9	69.3	85.0	79.8	73.6	69.0
6/18/54	85.5	81.8	76.0	70.2	88.2	82.0	75.0	69.6
6/21/54	85.8	81.8	76.8	71.2	90.9	83.9	77.4	71.6
6/22/54	85.4	82.0	76.9	71.6	88.4	82.8	77.6	72.6
6/23/54	86.4	82.0	76.2	71.6	91.6	83.6	76.2	71.8
6/24/54	86.0	81.6	76.6	72.0	92.2	84.4	77.4	72.6

	3	6	12	24	3	6	12	24
6/25/54	87.2	82.7	77.2	72.2	94.6	86.4	78.8	72.9
6/28/54	84.2	82.4	78.7	73.2	88.7	86.8	81.6	75.2
6/29/54	87.2	82.5	77.6	73.0	93.0	86.8	80.4	75.2
6/30/54	89.6	83.9	78.0	73.7	96.2	88.0	80.6	75.6

APPENDIX B

Table 46. Average daily resistance in ohms from the six soil moisture blocks at all depths and under each cover

Date	Grass				Fallow			
	Depth in inches				Depth in inches			
	3	6	12	24	3	6	12	24
6/12/53	321,000	36,300	2,950	580	1,310	890	880	570
6/15/53	992,000	237,000	4,570	630	1,310	940	910	580
6/16/53	1,343,000	429,000	9,800	650	1,540	970	940	580
6/17/53	1,450,000	822,000	13,800	670	1,380	970	980	590
6/18/53	1,693,000	1,040,000	21,900	720	1,390	990	1,000	590
6/19/53	1,690,000	1,200,000	38,200	780	1,410	1,020	1,020	600
6/20/53	1,920,000	1,320,000	63,800	860	1,420	1,040	1,040	590
6/21/53	1,980,000	1,340,000	103,000	920	1,580	1,060	1,060	600
6/22/53	1,933,000	1,440,000	165,000	1,030	1,510	1,080	1,080	610
6/23/53	2,100,000	1,650,000	247,000	1,170	1,590	1,100	1,100	620
6/25/53	329,500	1,430,000	462,000	1,630	1,610	1,170	1,160	640
6/26/53	2,850	525,000	352,000	2,030	1,250	1,000	1,080	630
6/27/53	3,380	544,000	317,000	2,420	1,290	990	1,050	600
6/28/53	79,500	468,000	418,000	3,110	1,150	960	1,010	600
6/29/53	74,280	409,000	415,000	3,530	1,450	1,060	1,100	650
6/30/53	93,670	638,000	463,000	4,060	1,580	1,130	1,150	670
7/ 1/53	152,000	663,000	463,000	5,390	1,570	1,130	1,170	670
7/ 2/53	509,800	834,000	547,000	6,620	1,540	1,140	1,200	680
7/ 3/53	993,000	1,000,000	588,000	8,730	1,540	1,200	1,220	690
7/ 4/53	1,300	1,130	1,170	1,640	820	720	1,050	630

	3	6	12	24	3	6	12	24
7/ 6/53	1,400	1,260	1,300	2,030	960	770	1,020	620
7/ 7/53	1,730	1,390	1,380	2,130	1,000	830	930	620
7/ 8/53	2,010	1,560	1,660	2,590	1,110	900	1,070	640
7/ 9/53	2,420	1,750	1,630	2,610	1,180	910	1,090	630
7/10/53	3,250	2,150	1,790	3,030	1,330	940	1,100	670
7/11/53	3,790	2,400	1,930	3,080	1,280	970	1,070	660
7/13/53	15,010	4,750	2,750	3,760	1,410	1,030	1,120	680
7/14/53	44,400	23,200	3,630	3,810	1,380	1,120	1,160	720
7/15/53	376,100	34,600	4,470	4,080	1,490	1,130	1,120	680
7/16/53	316,400	30,100	6,960	4,480	1,600	1,130	1,150	690
7/17/53	73,800	70,300	13,300	5,000	1,620	1,110	1,150	690
7/18/53	231,000	208,000	25,300	5,580	1,580	1,100	1,140	690
6/21/53	3,880	276,000	150,000	8,460	820	750	1,110	700
7/22/53	3,430	107,000	93,300	8,820	780	770	1,060	690
7/23/53	3,880	34,300	162,000	9,770	920	880	1,040	710
7/24/53	5,970	59,900	180,000	10,000	1,000	900	1,010	700
7/25/53	10,300	138,000	136,000	11,200	1,130	950	1,040	720
7/27/53	501,000	781,000	388,000	16,700	1,290	1,040	1,160	710
7/28/53	810,000	693,000	326,000	17,300	1,390	1,070	1,180	710
7/29/53	1,997,000	1,240,000	578,000	21,100	1,400	1,090	1,190	710
7/30/53	1,858,000	1,190,000	628,000	29,800	1,450	1,140	1,210	720
8/ 3/53	2,058,000	1,550,000	790,000	52,800	1,540	1,210	1,260	800
8/ 4/53	1,220	1,200	1,860	25,000	640	670	950	760
8/ 5/53	1,210	1,080	4,500	24,400	780	800	870	690
8/ 6/53	1,260	1,190	3,510	26,300	900	780	950	690
8/ 7/53	1,440	1,210	2,340	41,200	920	790	920	710
8/ 9/53	2,110	1,370	1,820	46,300	1,020	910	1,000	750
8/10/53	2,180	1,630	1,800	47,400	1,390	910	1,030	780
8/11/53	2,620	1,750	1,720	44,000	1,260	920	1,070	740
8/12/53	2,910	1,980	1,830	45,300	1,140	940	1,010	730

	3	6	12	24	3	6	12	24
8/13/53	3,460	2,360	1,820	44,000	1,130	970	1,060	720
8/15/53	6,600	3,330	2,070	44,100	1,270	960	990	750
8/16/53	8,060	4,380	2,310	49,700	1,210	1,090	1,070	730
8/17/53	11,980	5,450	2,570	44,800	1,280	1,160	1,150	730
8/18/53	24,680	7,200	2,830	38,200	1,240	1,110	1,150	730
8/19/53	77,100	10,800	3,180	42,800	1,250	1,090	1,160	720
8/20/53	278,450	23,000	4,060	48,400	1,280	1,100	1,180	710
8/21/53	524,900	38,600	5,240	43,400	1,260	1,120	1,130	740
8/22/53	807,150	111,000	5,870	43,600	1,280	1,130	1,140	750
8/24/53	1,240,000	505,000	17,133	53,000	1,430	1,200	1,220	770
8/25/53	1,420,000	463,000	32,500	57,000	1,470	1,200	1,170	780
8/26/53	1,600,000	753,000	66,300	63,900	1,490	1,190	1,160	780
8/27/53	1,712,000	1,060,000	80,400	59,200	1,520	1,250	1,140	780
8/29/53	1,740,000	1,180,000	467,000	58,600	1,510	1,290	1,200	790
8/30/53	1,750,000	1,220,000	497,000	103,000	1,530	1,310	1,150	790
8/31/53	1,965,000	1,270,000	423,000	77,300	1,700	1,290	1,130	800
9/ 1/53	2,075,000	1,460,000	543,000	97,400	1,640	1,330	1,210	790
9/ 2/53	1,750,000	1,310,000	515,000	138,500	1,600	1,330	1,220	800
9/ 4/53	1,160	1,030	177,000	85,900	800	630	640	630
9/ 5/53	1,190	1,080	44,600	79,400	850	730	860	630
9/ 7/53	1,450	1,220	11,700	91,300	900	750	920	700
9/ 8/53	1,640	1,340	8,180	69,900	970	790	920	730
9/ 9/53	2,300	1,560	8,460	67,300	1,040	820	890	750
9/10/53	2,290	2,090	5,910	71,800	970	860	890	730
9/11/53	2,700	1,810	6,320	32,300	1,140	810	920	790
9/12/53	3,350	2,090	5,790	89,000	1,020	780	850	780
9/14/53	3,600	2,670	2,290	73,500	1,120	840	890	760
9/15/53	7,120	3,340	5,620	75,300	1,180	900	910	760
9/16/53	8,850	3,800	6,310	83,200	1,180	930	940	780
9/17/53	17,800	5,350	7,410	78,100	1,260	990	990	820

	3	6	12	24	3	6	12	24
9/19/53	26,300	15,100	11,200	84,300	1,240	970	990	820
9/21/53	37,250	26,900	20,000	84,700	1,290	1,060	1,100	880
9/22/53	55,450	38,500	21,700	91,000	1,250	970	680	850
9/23/53	112,800	76,600	28,100	87,400	1,340	980	920	820
9/24/53	267,500	181,000	36,800	87,500	1,300	970	920	820
9/25/53	473,000	223,000	46,300	83,700	1,310	1,000	900	830
9/28/53	102,000	314,000	107,000	90,400	1,480	1,040	930	800
9/29/53	120,000	435,000	153,000	92,800	1,370	1,120	940	820
9/30/53	117,000	434,000	160,000	98,000	1,400	1,110	990	820
10/ 1/53	1,230,000	469,000	178,000	100,000	1,660	1,100	970	830
10/ 2/53	1,450,000	608,000	170,000	87,300	1,620	1,130	1,020	840
10/ 5/53	1,480	3,820	156,000	90,600	840	720	890	950
10/ 6/53	1,780	3,000	203,000	107,000	820	840	920	950
10/ 7/53	1,980	2,770	173,000	96,900	860	860	860	940
10/ 8/53	2,200	2,670	148,000	94,900	910	870	830	920
10/ 9/53	3,590	3,450	126,000	84,800	1,040	940	810	920
10/12/53	4,330	3,370	99,400	93,400	980	1,000	900	950
10/13/53	5,080	3,470	121,000	93,700	970	1,000	880	920
10/14/53	5,780	3,700	110,000	89,300	1,000	990	900	910
10/15/53	7,530	4,330	94,900	94,000	1,030	1,020	890	930
10/16/53	10,800	6,130	121,000	97,700	1,210	1,120	940	990
10/18/53	25,500	4,600	101,000	93,200	1,110	980	960	930
10/19/53	53,370	7,600	83,300	68,600	1,140	960	930	920
10/21/53	259,250	30,900	88,700	82,000	1,150	930	950	830
10/22/53	315,300	15,400	89,700	78,900	1,160	900	940	790
10/23/53	406,200	28,000	83,000	72,700	1,200	1,000	980	820
10/27/53	7,200	53,700	111,000	93,600	770	810	1,010	870
10/28/53	7,070	52,000	111,000	102,000	820	820	1,000	860
10/29/53	6,030	46,300	110,000	84,000	860	850	970	900
10/30/53	6,200	44,500	120,000	94,700	890	820	990	870

	3	6	12	24	3	6	12	24
11/ 2/53	7,570	41,500	116,000	90,400	1,060	910	1,010	830
11/ 3/53	7,900	43,200	124,000	91,200	1,080	960	1,050	820
11/ 4/53	8,870	38,500	118,000	86,100	1,040	960	1,030	820
11/ 5/53	8,950	42,900	127,000	92,300	1,070	990	1,030	820
11/ 6/53	9,720	45,000	127,000	92,000	1,020	1,020	1,030	810
11/ 9/53	13,400	54,700	124,000	96,800	1,280	1,090	1,120	810
11/10/53	19,140	61,300	128,000	92,300	1,310	1,120	1,130	810
11/11/53	27,860	67,300	128,000	88,000	1,340	1,150	1,130	810
11/12/53	47,800	80,000	128,000	85,800	1,360	1,180	1,130	810
11/13/53	74,330	142,000	128,000	86,200	1,440	1,160	1,110	790
11/17/53	730,000	281,000	129,000	94,200	1,410	1,200	1,140	790
11/18/53	730,000	325,000	140,000	140,500	1,410	1,210	1,150	800
11/20/53	12,500	332,000	172,000	97,100	780	850	1,210	800
11/23/53	6,830	292,000	150,000	108,000	960	900	1,080	810
11/24/53	6,890	138,000	149,000	104,700	990	920	1,100	810
11/25/53	6,950	138,000	149,000	103,100	1,020	950	1,100	810
11/27/53	7,140	138,000	148,000	102,000	1,080	1,020	1,110	830
11/28/53	7,120	138,000	148,000	99,600	1,100	1,050	1,120	830
11/30/53	7,220	138,000	148,000	98,700	1,170	1,120	1,130	850
12/ 1/53	7,260	138,000	152,000	101,000	1,170	1,150	1,150	850
12/ 3/53	4,730	97,000	162,000	108,000	930	1,060	1,200	840
12/ 4/53	4,180	97,000	155,000	100,000	930	1,060	1,210	840
12/ 7/53	3,940	47,700	154,000	101,000	1,020	1,060	1,180	870
12/ 8/53	3,990	38,500	155,000	100,000	1,010	1,070	1,170	880
12/10/53	4,220	37,500	177,000	108,000	1,010	1,130	1,200	880
12/11/53	4,480	35,000	188,000	112,000	1,020	1,150	1,210	880
12/15/53	5,350	35,000	188,000	120,000	1,060	1,180	1,240	900
12/16/53	5,650	35,000	188,000	122,000	1,060	1,180	1,250	910
12/17/53	5,970	35,000	188,000	124,000	1,070	1,190	1,260	910
12/18/53	6,320	35,000	188,000	126,000	1,080	1,190	1,260	910

	3	6	12	24	3	6	12	24
12/21/53	6,320	35,000	188,000	135,000	1,100	1,210	1,280	940
12/23/53	4,680	20,100	154,000	136,000	1,120	1,220	1,290	950
12/24/53	4,680	20,100	154,000	136,000	1,130	1,230	1,290	950
12/28/53	4,680	20,100	154,000	136,000	1,160	1,250	1,290	950
12/29/53	4,680	20,100	154,000	136,000	1,180	1,260	1,290	950
12/30/53	4,680	20,100	154,000	136,000	1,180	1,260	1,290	950
12/31/53	4,680	20,100	154,000	136,000	1,180	1,260	1,290	950
1/ 1/54	4,680	20,100	154,000	136,000	1,190	1,260	1,290	950
1/ 2/54	4,680	20,100	154,000	136,000	1,190	1,260	1,290	950
1/ 4/54	4,680	20,100	154,000	136,000	1,200	1,260	1,290	950
1/ 5/54	4,680	20,100	154,000	136,000	1,210	1,260	1,290	950
1/ 6/54	4,680	20,100	154,000	136,000	1,220	1,260	1,290	950
1/ 7/54	4,680	20,100	154,000	136,000	1,220	1,260	1,290	950
1/ 8/54	4,680	20,100	154,000	136,000	1,220	1,260	1,290	950
1/ 9/54	4,680	20,100	154,000	136,000	1,230	1,260	1,290	950
1/11/54	4,680	20,100	154,000	136,000	1,200	1,260	1,290	950
1/13/54	4,680	20,100	154,000	136,000	1,210	1,260	1,290	950
1/14/54	4,680	20,100	154,000	136,000	1,220	1,260	1,290	950
1/15/54	4,680	20,100	154,000	136,000	1,220	1,260	1,290	950
1/17/54	4,680	20,100	154,000	136,000	1,260	1,260	1,290	950
1/18/54	4,680	20,100	154,000	136,000	1,270	1,260	1,290	950
1/19/54	4,680	20,100	154,000	136,000	1,270	1,260	1,290	950
1/21/54	3,570	2,620	27,100	48,700	1,280	1,260	1,100	950
1/22/54	3,570	2,620	27,100	48,700	1,280	1,260	1,100	950
1/23/54	3,310	2,620	27,100	48,700	1,290	1,260	1,100	950
1/25/54	2,890	2,620	27,100	48,700	1,300	1,260	1,100	950
1/27/54	2,770	2,620	27,100	48,700	1,310	1,090	1,100	760
1/28/54	2,770	2,620	27,100	48,700	1,320	1,090	1,100	760
1/29/54	2,770	2,620	27,100	48,700	1,320	1,090	1,100	760
1/30/54	3,770	2,620	27,100	48,700	1,320	1,090	1,100	760

	3	6	12	24	3	6	12	24
2/ 1/54	2.770	2.620	27,100	48,700	1,320	1,090	1,100	760
2/ 2/54	2,770	2,620	27,100	48,700	1,320	1,090	1,100	760
2/ 3/54	2,770	2,620	27,100	48,700	1,330	1,090	1,100	760
2/ 4/54	2,770	2,620	27,100	48,700	1,340	1,090	1,100	760
2/ 5/54	2,770	2,620	27,100	48,700	1,340	1,090	1,100	760
2/ 7/54	2,770	2,620	27,100	48,700	1,350	1,090	1,100	760
2/ 8/54	2,770	2,620	27,100	48,700	1,350	1,090	1,100	760
2/ 9/54	2,770	2,620	27,100	48,700	1,360	1,090	1,100	760
2/10/54	2,770	2,620	27,100	48,700	1,360	1,090	1,100	760
2/11/54	2,770	2,620	27,100	48,700	1,370	1,090	1,100	760
2/12/54	2,770	2,620	27,100	48,700	1,380	1,090	1,100	760
2/15/54	2,770	2,620	27,100	48,700	1,390	1,090	1,100	760
2/16/54	1,260	1,510	22,200	55,200	780	770	1,070	770
2/17/54	1,260	1,510	22,200	54,700	790	770	1,030	780
2/18/54	1,310	1,510	9,900	53,800	800	780	1,030	780
2/22/54	1,420	1,370	9,900	53,000	880	840	990	780
2/23/54	1,460	1,370	9,900	52,600	900	850	970	780
2/24/54	1,540	1,370	9,900	52,300	930	870	960	780
2/26/54	1,540	1,370	9,900	52,300	910	880	930	780
3/ 1/54	1,540	1,440	2,420	52,400	900	920	1,000	790
3/ 4/54	1,490	1,440	2,420	52,400	920	940	1,000	790
3/ 5/54	1,520	1,440	2,420	52,400	930	960	1,000	800
3/ 7/54	1,560	1,440	2,420	52,500	950	970	1,000	800
3/ 8/54	1,630	1,440	2,420	52,500	960	990	1,000	800
3/ 9/54	1,650	1,440	2,420	52,500	960	1,000	1,000	800
3/11/54	1,740	1,440	2,420	52,600	990	1,010	1,000	800
3/12/54	1,740	1,440	2,420	52,600	990	1,010	1,000	800
3/15/54	1,740	1,440	2,420	52,600	990	1,010	1,000	800
3/16/54	1,740	1,440	2,420	52,600	990	1,010	1,000	800
3/17/54	1,740	1,440	2,420	52,600	990	1,010	1,000	800

	3	6	12	24	3	6	12	24
3/19/54	1,200	1,070	1,130	40,900	780	800	910	800
3/22/54	1,200	1,070	1,130	40,900	780	800	910	780
3/24/54	1,200	1,070	1,130	40,900	780	800	910	770
3/25/54	1,200	1,070	1,130	40,900	780	800	910	760
3/26/54	1,200	1,070	1,130	40,900	780	800	910	750
3/27/54	1,320	1,090	1,100	39,900	820	820	910	760
3/28/54	1,500	1,160	1,110	39,200	860	840	920	760
3/29/54	1,640	1,230	1,120	38,900	900	850	930	770
3/30/54	1,860	1,300	1,130	37,100	940	880	930	770
3/31/54	2,020	1,370	1,140	37,100	9[illegible]0	[illegible]90	940	770
4/ 1/54	2,280	1,450	1,150	37,100	1,020	920	940	780
4/ 2/54	2,570	1,640	1,160	36,800	1,060	940	940	780
4/ 5/54	3,700	1,840	1,200	35,700	1,180	1,000	960	790
4/ 6/54	3,700	1,960	1,200	36,100	1,180	1,000	960	790
4/ 7/54	3,700	2,050	1,200	37,300	1,180	1,000	960	790
4/ 8/54	3,700	2,170	1,200	38,600	1,180	1,000	960	790
4/ 9/54	3,700	2,290	1,200	40,200	1,180	1,000	960	800
4/10/54	3,450	2,330	1,200	41,200	1,180	1,000	960	800
4/12/54	3,450	2,330	1,350	44,800	890	850	920	790
4/13/54	3,450	2,330	1,430	44,800	880	850	920	790
4/15/54	5,840	3,870	1,490	42,700	880	860	920	780
4/17/54	10,100	3,870	1,550	42,000	880	870	920	770
4/20/54	23,600	3,870	1,650	42,000	900	880	910	770
4/22/54	1,020	900	820	37,800	540	580	580	590
4/23/54	1,080	940	770	39,400	580	610	570	560
4/26/54	1,170	990	840	40,400	770	650	660	520
4/27/54	1,140	940	840	37,400	720	650	660	580
4/28/54	1,180	960	820	38,400	720	650	660	580
4/29/54	1,210	1,000	820	40,400	720	650	660	580
5/ 3/54	930	780	720	560	610	620	570	520

	3	6	12	24	3	6	12	24
5/ 4/54	930	780	720	560	660	620	570	510
5/ 5/54	950	860	710	610	700	620	570	490
5/ 6/54	910	810	720	610	700	620	570	490
5/ 7/54	940	810	710	610	700	630	570	490
5/10/54	1,070	870	730	560	810	660	580	520
5/11/54	1,240	950	730	570	860	680	590	530
5/12/54	1,400	1,010	730	570	890	700	600	530
5/13/54	1,740	1,050	770	570	960	740	610	550
5/14/54	2,130	1,150	780	570	1,130	760	630	540
5/17/54	2,550	1,360	850	580	1,070	830	670	580
5/18/54	3,160	1,500	900	560	1,110	860	680	590
5/19/54	3,080	1,630	930	580	1,200	890	700	620
5/20/54	3,700	1,790	960	570	1,270	910	710	590
5/21/54	4,870	1,900	1,000	560	1,400	950	720	580
5/24/54	1,200	970	760	530	760	630	570	480
5/25/54	1,300	930	780	550	790	640	570	500
5/26/54	1,380	960	750	540	810	550	580	520
5/27/54	1,460	1,000	760	530	870	660	570	510
5/28/54	1,370	850	620	530	880	660	540	510
5/31/54	1,370	850	600	470	770	613	520	510
6/ 1/54	980	740	590	470	730	590	450	520
6/ 2/54	970	670	560	470	670	590	460	490
6/ 3/54	850	680	560	470	670	590	460	470
6/ 4/54	850	690	560	470	690	590	470	440
6/ 7/54	930	820	630	460	780	620	500	470
7/ 8/54	930	830	640	460	810	640	520	470
6/ 9/54	690	610	540	460	650	560	450	490
6/10/54	790	690	550	440	680	570	460	480
6/11/54	830	720	610	460	700	590	480	480
6/14/54	930	800	650	490	790	660	530	490

	3	6	12	24	3	6	12	24
6/15/54	900	800	670	470	780	650	530	490
6/16/54	1,050	820	660	490	860	690	550	500
6/17/54	1,210	930	710	490	920	750	560	530
6/18/54	1,380	990	750	490	940	760	570	520
6/21/54	2,970	1,390	890	480	1,030	800	600	530
6/22/54	2,820	1,630	930	490	990	800	600	540
6/23/54	4,240	1,860	960	500	1,040	800	630	550
6/24/54	7,030	2,290	1,040	490	1,110	840	660	560
6/25/54	14,950	3,080	1,100	530	1,190	910	670	560
6/28/54	196,000	15,700	1,620	510	1,360	1,080	680	550
6/29/54	411,670	31,200	1,910	520	1,440	1,100	710	580
6/30/54	720,000	64,000	2,420	550	1,510	1,130	730	600